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Volume I. Sections I thru VIII

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This two-volume report presents a summary of the state-of-the-art of aquifer restoration. Included are eight sections and seven appendices. The text includes sections on: (1) ground water pollution control through institutional measures, source control, stabilization/solidification methods, well systems, interceptor systems, capping and liners, sheet piling, grouting and slurry walls; (2) treatment of ground water via air stripping, carbon adsorption, biological treatment, chemical precipitation, and other treatment techniques; (3) in-situ chemical treatment and biological stabilization; (4) a protocol for aquifer restoration decision-making; and (5) techniques for aiding the decision-making process. The appendices (volume II) include: (1) case studies of aquifer restoration; (2) considerations regarding an aquifer restoration information center; (3) information for public participation in aquifer restoration decision-making; and (4) an annotated bibliography of 225 selected references. The stat-of-the-art of aquifer restoration is a rapidly changing technology, with many uses of single or combined techniques in planning or recently implemented. Unfortunately, few if any systems have yet reached shut-down levels for contaminants. Thus, effectiveness, duration and cost data are as yet incomplete but highly encouraging. A major need is for a systematic and comprehensive study of the cost-effectiveness of aquifer restoration technologies.

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a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Ground Water	Water Treatment	Clean-up	68D
Ground Water Recharge	Water Reclamation	Remedial Actions	91A
Aquifers		Restoration	50B
Geology	Abatement	In-Situ Treatment	68C
Contaminants	Waste Disposal	Air-stripping	
Water Pollution		Biological Clean-up	
Decontamination		Slurry Walls	
		Barrier Wells	

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FOREWORD

EPA is charged by Congress to protect the Nation's land, air and water systems. Under a mandate of national environmental laws focused on air and water quality, solid waste management and the control of toxic substances, pesticides, noise, and radiation, the Agency strives to formulate and implement actions which lead to a compatible balance between human activities and the ability of natural systems to support and nurture life.

The Robert S. Kerr Environmental Research Laboratory is the Agency's center of expertise for investigation of the soil and subsurface environment. Personnel at the laboratory are responsible for management of research programs to: (a) determine the fate, transport and transformation rates of pollutants in the soil, the unsaturated zone and the saturated zones of the subsurface environment; (b) define the processes to be used in characterizing the soil and subsurface environment as a receptor of pollutants; (c) develop techniques for predicting the effect of pollutants on ground water, soil and indigenous organisms; and (d) define and demonstrate the applicability and limitations of using natural processes, indigenous to the soil and subsurface environment, for the protection of this resource.

This project was initiated to provide a state-of-knowledge document of ground-water restoration methods describing available technologies and their applicability, and comparing methodologies and relative costs vs alternatives to restoration. The information found has been grouped into two volumes and includes sections on: (1) ground-water pollution control, (2) treatment of ground water, (3) in situ treatment, (4) a protocol for aquifer restoration decision-making, and (5) techniques for decision-making processes. The appendices include case studies of aquifer restoration and an annotated bibliography of 225 selected references. This compilation should be useful to those having a need for information about the cost-effectiveness of aquifer restoration technologies.

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ABSTRACT

This two-volume report presents a summary of the state-of-the-art of aquifer restoration. Included are eight sections and seven appendices. The text includes sections on: (1) ground water pollution control through institutional measures, source control, stabilization/solidification methods, well systems, interceptor systems, capping and liners, sheet piling, grouting and slurry walls; (2) treatment of ground water via air stripping, carbon adsorption, biological treatment, chemical precipitation, and other treatment techniques; (3) in-situ chemical treatment and biological stabilization; (4) a protocol for aquifer restoration decision-making; and (5) techniques for aiding the decision-making process. The appendices (volume II) include: (1) case studies of aquifer restoration; (2) considerations regarding an aquifer restoration information center; (3) information for public participation in aquifer restoration decision-making; and (4) an annotated bibliography of 225 selected references. The state-of-the-art of aquifer restoration is a rapidly changing technology, with many uses of single or combined techniques in planning or recently implemented. Unfortunately, few if any systems have yet reached shut-down levels for contaminants. Thus, effectiveness, duration and cost data are as yet incomplete but highly encouraging. A major need is for a systematic and comprehensive study of the cost-effectiveness of aquifer restoration technologies.

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SECTION I

INTRODUCTION

Pollution of ground water can result from many activities, including leaching from municipal and chemical landfills and abandoned dump sites, accidental spills of chemicals or waste materials, improper underground injection of liquid wastes, and placement of septic tank systems in hydrologically and geologically unsuitable locations. In recent years incidents of aquifer pollution from man's waste disposal activities have been discovered with increasing regularity. Concurrently, demands for ground water usage have been increasing due to population growth and diminishing opportunities to economically develop surface water supplies. Until recently the general viewpoint held by many ground water professionals and policy-makers was that once an aquifer had become polluted its water usage must be curtailed or possibly eliminated. However, this viewpoint is changing as a result of increasing needs for ground water utilization and the development of appropriate methodologies for aquifer clean-up. The focus on methodologies has been heightened by current hazardous waste site clean-up efforts funded by "Superfund".

CLASSIFICATION OF METHODOLOGIES

Table I.1 lists methodologies for aquifer clean-up organized according to whether the pollution problem is acute or chronic. Acute pollution may occur from inadvertent spills of chemicals or releases of undesirable materials and chemicals during a transportation accident. Acute pollution events are unplanned and are characterized by their

Table I.1: Methodologies for Aquifer Clean-up

Pollution Problem	Goal	Methodologies
Acute	Abatement	1. In-situ chemical fixation. 2. Excavation of contaminated soil with subsequent backfilling with "clean" soil.
	Restoration	1. Removal wells, treatment of contaminated ground water, and recharge. 2. Removal wells, treatment of contaminated ground water, and discharge to surface drainage. 3. Removal wells and discharge to surface drainage.
Chronic	Abatement	1. In-situ chemical fixation. 2. Excavation of contaminated soil with subsequent backfilling with "clean" soil. 3. Interceptor trenches to collect polluted water as it moves laterally away from site. 4. Surface capping with impermeable material to inhibit infiltration of leachate-producing precipitation. 5. Subsurface barriers of impermeable materials to restrict hydraulic flow from sources. 6. Modify pumping patterns at existing wells. 7. Inject fresh water in a series of wells placed around source or contaminant plume to develop pressure ridge to restrict movement of pollutants.

Table I.1 (continued)

Pollution Problem	Goal	Methodologies
Chronic	Restoration	1. Removal wells, treatment of contaminated ground water, and recharge. 2. Removal wells, treatment of contaminated ground water, and discharge to surface drainage. 3. Removal wells and discharge to surface drainage. 4. In-situ chemical treatment. 5. In-situ biological treatment.

emergency nature. Chronic aquifer pollution may occur from numerous point and area sources and may involve traditional pollutants such as nitrates and bacteria, or unique pollutants such as gasoline, metals, and synthetic organic chemicals.

Methodologies for aquifer clean-up can also be considered in terms of the goals of abatement and restoration. Abatement means "to put an end to"; therefore, abatement as a goal refers to the application of methodologies which will aid in preventing pollutant movement into ground water, or preventing contaminated plume movement into usable aquifer zones. The latter example of abatement is also called plume management. Aquifer restoration as a goal refers to the restoration of water quality to its normal quality, usually by removing both the source of pollution and renovating the polluted ground water. If the pollution source has already been dissipated by time, restoration may only involve renovation of the polluted ground water.

It should be noted that a given aquifer clean-up project may involve usage of several methodologies in combination. For example, for an acute problem, excavation and backfilling may be used in conjunction with removal wells, treatment of contaminated ground water, and discharge to surface drainage. A chronic pollution clean-up project may include surface capping, subsurface barriers, and in-situ chemical treatment.

OVERVIEW STUDIES

In 1977, Lindorff and Cartwright surveyed the nation for case histories of aquifer clean-up. Information on 116 cases of aquifer pollution was summarized, with most of the pollution either caused by industrial wastes or by leaching from municipal landfills. Table I.2 summarizes the clean-up methodologies used in 32 of the cases (Lindorff and Cartwright, 1977). Removal wells are best applied when the pollution has not traveled far from the source, and they have most often been used to remove oil and oil products. This technique has also been used to control water soluble chemicals. For oil pollution two or more pumping locations in each well may be used, a deep pump to maintain a drawdown cone and a shallow skimming pump to remove the oil (Todd, 1973). For pollutants that have traveled very far from the source or have dispersed, the use of interceptor trenches is often more effective than the drawdown cone in a removal well. The interceptor trench (or pit or ditch) is placed across the pollution plume to capture the ground water flow. The water is then pumped out and treated. This method is obviously most useful for shallow aquifers (Committee on Environmental Affairs, 1972).

From May to October, 1980, a survey of on-going and completed remedial action projects was conducted by Neely, et al. A total of 169 hazardous waste sites were identified; however, because controls for ground water clean-up are more expensive and time consuming than those for surface water, complete remedial measures were implemented at only a few sites. Details of remedial measures were reported for nine selected sites, with the measures appearing to be effective at only two sites (Neely, et al., 1981).

An expert seminar was held in Paris, France in November, 1980, under sponsorship of the Organization for Economic Co-operation and

Table I.2: Aquifer Clean-up Survey (Lindorff and Cartwright, 1977)

Remedial Action	State	Ground Water Pollutant or Source
Removal wells	California	gasoline
	Delaware	landfilling
	Georgia	gasoline
	Illinois	acrylonitrile chemical wastes cyanide
	Indiana	acetone cyanohydrin oil
	Kentucky	hydrochloric acid
	Michigan	industrial waste pond
	Minnesota	solvents and acids
	New Jersey	chromium heavy metals
	New Mexico	chlorides
	New York	gasoline
	Ohio	brines chlorides
	Oregon	aluminum and mine tailings
	Pennsylvania	fuel oil gasoline insecticides terpenes and acids
	Wisconsin	organic wastes sulfite liquor
Removal wells and treatment	California	phenols (a)
	Connecticut	styrene (b)
	New Jersey	petrochemicals (b)

Table I.2 (continued)

Remedial Action	State	Ground Water Pollutant or Source
Interception trench	Georgia	gasoline
	Idaho	cadmium, lead, and zinc
	Pennsylvania	fuel oil landfill
	South Dakota	landfill

(a) treatment with chlorine dioxide

(b) treatment with activated carbon filters

Development (OECD). Table I.3 summarizes remedial actions used at 13 sites, including 5 from the USA, 4 from Germany, and one each from France, The Netherlands, Sweden, and the United Kingdom (Organization for Economic Co-operation and Development, 1983). One conclusion from the seminar was that a careful evaluation of the cost-effectiveness of possible remedial measures is essential before decisions are made with regard to implementation of a particular methodology. All components of the cost of a remedial program must be taken into account. These include, in addition to the actual engineering cost, the physicochemical site evaluation required prior to implementation of remedial measures and the subsequent monitoring. It is possible that the cost of prior evaluation and subsequent monitoring may equal that of the remedial methodology used.

As a result of these overview studies, three generalizations about aquifer restoration strategies can be made. First, they are costly. Restoration often costs tens of millions of dollars. Secondly, they are time-consuming. Because most problems have been recognized only after the pollutant has been moving and spreading for a number of years, the areal extent of pollution is often quite large. Consequently, it takes a long time to clean up these large problems. Third, aquifer restoration strategies are not always effective. Although the success ratio of recent years has increased, there are a number of instances where the clean-up strategy has been ineffective and second and third attempts to restore the aquifer have been made.

Table I.3: Examples of Aquifer Clean-up Projects (Organization for Economic Cooperation and Development, (1983).

	Brief Site Description	Nature of "Problem"	Remedial Action	Comments
1.	West Germany, Hamburg Contamination, mainly heavy metals detected in 1978 at a central decontamination plant in an industrial area. The 100 m^2 area contained 100 m^3 of contaminated material.	Soil and groundwater contamination shown by drilling and sampling.	Removal of contaminated soil to hazardous waste disposal site. Pumping of groundwater.	
2.	La Bounty Dump, Charles City, Iowa, USA Chemical waste dump operated in river flood plain over major aquifer, 1952-1977. Contained over 3 million tons of feed additives and veterinary pharmaceuticals including 28 priority pollutants.	Pollution of river.	Monitoring and closure of site with a "capping". Some in situ stabilization may follow.	If remedial action is not effective enough, an up gradient cut-off wall may be installed to reduce water flow.
3.	Windham, Connecticut, USA Landfill to Willimatic Township	Groundwater pollution and threatened public water supply reservoir.	PVC Cap installed to prevent rain water inflow to refuse. Site closed.	90% of water to be intercepted and routed away.
4.	Clin Corporation Site, Saltville, PA., USA Mercury wastes from nearby alkali industry.	Mercury globules visible at surface. River polluted. Vapour hazard.	Temporary cosmetic treatment to reduce immediate hazard by covering exposed waste near river with plastic and sand to reduce pollution to river.	Only satisfactory solution is a \$23 million removal operation. Recovery of mercury currently not economic because of price slump.
5.	Firestone Tire and Rubber Site, Pottstown, PA., USA Tires, scrubber waste, organic waste, pigments, and PVC sludge.	Unknown.	Recovery wells to intercept polluted water and recycle it through plant.	100% efficient solution is the problem anticipated. Length of pumping and costs not quoted.
6.	Various locations in USA Sites containing solvents, oils, paint wastes, heavy metals, acid sludges and PCBs.	Toxic liquid lagoons. Leachate surface migration. Leachate spread.	Techniques include: removal of waste at the site; containment of waste at the site; emptying of pits/lagoons; oil absorption in fuller's earth; mobile active carbon unit.	Many cases had received temporary remedial treatment and were awaiting funds before complete remedial work could be carried out.

Table I.3: (continued)

7.	City of Hamburg, Germany Toluene contamination from 700 m^3 of waste reached 100 m^2 of subway in the marketing area of the city.	Damage to concrete of subway. Soil and groundwater contamination. Toluene vapour.	Reconstruction of part of tunnel shown by drilling and sampling to be in contaminated area. Removal of soil to proper landfill site. Three years ground water pumping.	
8.	Grenzach Wyllen, Germany Disposal of chlorinated hydrocarbons, chemical warfare agents in gravel pit.	Chlorinated hydrocarbons in drinking water. Highly toxic material.	----------	Development of special investigation and analyses methods.
9.	Marals de Ponteau, France 30,000 m^3 of oil waste on salt	Surface water contamination aesthetic insult.	Removal, incineration and solidification.	Cost - 6 million francs. Successful solidification.
10.	Lekkerkerk, Netherlands Houses built on chemical waste with high solvent content.	Contamination of drinking water and air.	Total removal, incineration and disposal.	High cost, evacuation of residents necessary.
11.	R.T. Kemi, Sweden Large-scale disposal of pesticides in agricultural region near surface water.	Surface water contamination, odors, and possible public health impacts.	Water management, excavation and incineration.	Experience in groundwater purging. Heavy participation by public and media.
12.	Malkins Bank, United Kingdom General industrial waste tip in rural area.	Noxious odors, surface water contamination.	Encapsulation and restoration to public golf course.	Private land acquired by government.
13.	Gendorf, Germany Organics and other pesticides on production site.	Soil, groundwater and surface water contamination.	Encapsulation, surface sealing and solidification.	Excavation too dangerous. Permanent restrictions on land use.

OBJECTIVE OF THIS STUDY

The major objective of this study was to conduct a state-of-the-art survey of aquifer restoration in the United States. Emphasis was given to the assemblage of information on technologies available for the prevention, abatement, clean-up and restoration of polluted ground water formations. In addition, a structured approach or protocol for the selection of aquifer restoration strategies was developed.

SCOPE OF STUDY

The scope of the study reported herein primarily involved the conduction of a review and analysis of published literature on aquifer restoration. In addition, visits were made to several ground water-oriented organizations to gather information. A nation-wide survey of consulting firms was also conducted. Probably the single most constructive activity, in terms of information accumulation, was the attendance at, participation in, or conduction of, several conferences dealing in whole or in part with aquifer restoration.

ORGANIZATION OF REPORT

This report consists of eight sections and seven appendices organized into two volumes. The first volume contains the eight sections, while the second volume contains the appendices. In addition to this introductory section, the other section titles are as follows:

Sec. II -- Conclusions
Sec. III -- Recommendations
Sec. IV -- Ground Water Pollution Control
Sec. V -- Treatment of Ground Water

Sec. VI -- In-situ Technologies

Sec. VII -- Protocol for Aquifer Restoration Decision-Making

Sec. VIII -- Techniques for Decision-Making

The topical coverages of the appendices are as follows:

App. A -- Case Studies of Aquifer Restoration Measures

App. B -- Considerations Related to Aquifer Restoration Information Center

App. C -- Air Stripping of Volatile Organics from Ground Water

App. D -- Activated Carbon Adsorption of Organics from Ground Water

App. E -- Public Participation in Aquifer Restoration Decision-Making

App. F -- Risk Assessment as Related to Aquifer Restoration Planning

App. G -- Annotated Bibliography for Aquifer Restoration (a total of 225 references are included).

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SECTION II

CONCLUSIONS

As recently as the late 1970's, the four most common perceptions concerning aquifer restoration measures were: (1) they were costly; (2) they were time-consuming; (3) they were not always effective; and (4) pertinent information was unavailable. Although these perceptions have not been totally reversed, the state-of-the-art is significantly different. There has been an ever-increasing amount of information becoming available concerning aquifer restoration and ground water cleanup. The majority of this recent information has been presented in a wide variety of conferences and symposia. However, the amount of information published in the refereed literature remains sparce, and a significant amount of information also remains unavailable because it is associated with litigation. This section summarizes the findings and conclusions of this state-of-the art study of aquifer restoration.

Many different measures, ranging from institutional mandates to physical technologies, have been proposed for the protection and/or cleanup of ground water resources. Institutional measures actually implemented consist mainly of legislated authority to enforce cleanup mandates. In addition, a number of states have developed preventive policies such as requiring liners and/or surface water control at waste disposal facilities. Several Federal institutional measures have provisions for addressing the protection or cleanup of ground water, including the Comprehensive Environmental Response, Compensation and

Liability Act (Superfund), the Safe Drinking Water Act, the Underground Injection Control Program, and others.

The large number of physical technologies proposed for the cleanup of polluted ground water have come from several disciplines. The traditional hydrogeological technology of pumping wells has been supplemented by technologies from civil engineering and construction industries such as grouting and slurry walls; and from the agricultural industry which has provided subsurface drainage technologies. At any one site, the remedial program employed will usually consist of a combination of technologies. Not all of the technologies have been tried or proven for ground water pollution applications, and performance data for these new applications is just now becoming available.

In spite of the innovative technologies now being promoted, the most popular ground water cleanup measure consists of removal and treatment. The mechanics of ground water flow to removal wells have been studied for a number of years. This knowledge is most often combined with traditional wastewater treatment technologies to clean up a polluted aquifer. In fact, this mode of cleanup has become so common that there is increased interest and study toward developing compact, mobile wastewater treatment units; especially units for organics removal by adsorption or air stripping.

Treatment of polluted ground water by in-situ techniques is still in its infancy; however, it is receiving increased attention. Successful in-situ treatment is highly dependent on both the characteristics of the pollution(s) and the subsurface hydrogeology. Examples of studies with adequate controls to determine the effectiveness of in-situ techniques are limited, but it is recognized that in-situ techniques will be applicable only to sites meeting highly specific requirements.

The costs of aquifer restoration measures are dependent on many factors. Published information concerning cost of remedial techniques has most often been reported as unit cost data or national average costs. However, from the few specific reports on economics and consideration of several case studies, one significant conclusion can be drawn. The conclusion is that the cost of cleaning up an aquifer will not always be in the tens of millions of dollars. Not all aquifer restoration projects will fall under the Superfund category which has received so much publicity for its large expenditures. In fact, some examples of successful and economic aquifer cleanup projects using private funds have been identified.

Development of feasible strategies (alternatives) from potential aquifer restoration measures also depends on many factors. In developing a set of alternatives, it is necessary to consider the total system and to include future preventive measures in addition to current cleanup activities. Because ground water pollution is not strictly a hydrogeologic problem, proposed solutions require the consideration of a multi-disciplinary team. A comprehensive preliminary study is necessary to catalog existing information, thus eliminating duplication of effort; and to prevent the immediate implementation of poorly planned alternatives which can be ineffective. The development of a list of alternative remedial measures, following the preliminary study, should be based on an iterative process. By iterating through the selection process, measures can be refined in order to minimize design flaws which may go undetected in the subsurface environment.

Selection of a single aquifer restoration strategy from a list of alternative measures requires balanced consideration of the economic, environmental and risk implications of each alternative. In evaluating the economics of a remedial measure it is important to include all costs and to convert all costs to a common time period. Environmental evaluations should recognize any irretrievable commitments of the subsurface environment, and the finite life expectancy of some measures such as liners. Risk assessment is a new field of study and as such, there are few available methodologies and a dearth of risk data. A proper risk assessment methodology should utilize minimal amounts of estimated input data and produce replicable results.

A myriad of techniques are available for aiding decision-making based on a balanced and systematic consideration of the economic, environmental and risk features of feasible alternatives. Any technique used should include public participation as an integral component. Because of adverse publicity given such sites as Love Canal, Valley of the Drums, and Times Beach, the public has become extremely concerned over sites with the potential for contaminating their drinking (ground) water supplies. A number of procedures for incorporating public input in decision-making are available.

SECTION III

RECOMMENDATIONS

Based upon this study of the state-of-the-art of aquifer restoration, seven recommendations have been formulated as follows:

(1) Systematic Research Program -- There is a need for development of a systematic research program aimed at increased understanding of the behavior and effectiveness of various remedial measures. Outlined in Table III.1 is an example list of the most immediate research needs concerning aquifer restoration measures.

(2) Aquifer Restoration Information Center -- The need for a centralized aquifer restoration information dissemination center cannot be overemphasized. Currently, information directly related to ground water quality control and cleanup is being generated from a large number of widely dispersed activities. Additionally, extant and informative material can be found in sources somewhat related but not directly applied to ground water. An aquifer restoration information center could centralize available and pertinent information. The centralized information could be categorized according to sources, pollutants, remedial measures employed, costs, and effectiveness. The centralized and categorized information could be disseminated much more efficiently.

In addition to information on cases of ground water pollution cleanup there is a need for cataloging the growing number of professionals and/or companies providing services related to ground water quality management. This catalog should also be categorized according to area of experience and expertise.

In addition to national conferences and symposia, there should be developed intensive short courses or workshops devoted solely to the technical aspects of aquifer restoration. Although geographically dispersed, these courses could be conducted through the aquifer restoration information center.

(3) Monitoring -- One aspect of remedial measure design that is also receiving increased interest is ground water quality monitoring. Most remedial measures are designed, at least in part, on the basis of pre-existing monitoring data. All remedial measures should include, as an integral component of their design, provisions for monitoring the long-term effectiveness of the measures employed.

Table III.1: Examples of Aquifer Restoration Research Needs

Topical Area	Specific Needs
Surface Capping and Liners	1. Development of standardized tests for assessment of in-place integrity.
	2. Development of accelerted testing procedures for assessing the long-term performance of liners and seals.
	3. Effects of root-penetration on surface caps.
Slurry Walls	1. Effects of organics on bentonite -- change in bentonite properties and migration of organics through bentonite over time.
	2. Effects of organics on various bentonite-cement mixtures -- change in properties of mixtures (e.g., shrink-swell potential) and migration of organics through the mixtures over time.
	3. Development of techniques for assessing the in-place integrity of slurry walls. (permeability, bottom connections, seepage, etc.).
Air Stripping of Volatile Organics from Ground Water	1. Stripping of single compounds vs. mixtures of compounds.
	2. Stripping characteristics of different classes of volatile organics.
	3. Direct or indirect (fouling of packing media) interferences of ground water constituents on stripping. Examples include metals (Fe, Mn, Cr), inorganic salts (TDS), % saturation of oxygen, nonvolatile organics, and microbial activity.

Table III.1: (continued)

Topical Area	Specific Needs
	4. Effectiveness of batch vs. continuous vs. combination (batch and continuous) stripping.
	5. Effectiveness of natural desorption vs. mechanical stirring.
	6. Use of Total Organic Carbon (TOC) and COD as a surrogate indicator of volatile organics.
	7. Effects of concentrations of volatile organics on stripping.
	8. Use of simulated vs. actual ground water for treatability studies.
	9. Optimization of packed tower design in terms of packing type and size, detention time, air/water ratio, height of packing, temperature and variations, moving gas (air, oxygen, ozone), stripping enhancement via chemical additions, counter-current vs. cross-current vs. co-current flow, no packing, single tower vs. towers in series, scale-up from laboratory studies to pilot plants to full design, and development of computer-based design program.
	10. Atmospheric dispersion of released organics.
	11. Cost-effectiveness studies of existing facilties.
Removal of Organics via Activated Carbon Treatment	1. Adsorption of single compounds vs. mixtures of compounds.
	2. Adsorption characteristics of different classes of compounds.

Table III.1: (continued)

Topical Area	Specific Needs
	3. Direct or indirect (fouling of activated carbon) interferences of ground water constituents on adsorption. Examples include: metals (Fe, Mn, Cr), inorganic salts (TDS), % saturation of oxygen, nonvolatile organics, and microbial activity.
	4. Use of TOC and COD as surrogate indicator of adsorbable organics.
	5. Effects of concentrations of adsorbable organics on adsorption.
	6. Use of simulated vs. actual ground water for treatability studies.
	7. Optimization of activated carbon column design in terms of: size of carbon, detention time, column diameter, depth of carbon, temperature and variations, adsorption enhancement via chemical additions, single column vs. columns in series, scale up from laboratory studies to pilot plants to full design, and development of computer-based design program.
	8. Cost-effectiveness studies of existing facilities.

(4) Costs -- The costs of remedial measures is an area that is severely lacking in comprehensive and transferrable information. Information on the over-all cost-effectiveness of remedial measures, including the long-term operation, maintenance and monitoring costs, is needed. A research effort based on a case study approach should be conducted to develop cost-effective information.

(5) Remedial Measure Selection -- All future remedial measures should be designed and selected based on the application of a structured decision-making methodology or protocol. The methodology should include provisions for public participation. The approach utilized should be documented and technically defensible. Progress in the field of remedial measure design and selection cannot proceed based only on an analysis of previous cases developed by ad hoc procedures.

(6) Risk Assessment Methodologies -- There is a need for development of risk assessment methodologies that can aid in evaluating the need for and effectiveness of cleanup measures. Additionally, methodologies need to be developed that are simple in theory, easy to apply, and utilize available data. Methodologies involving complex stochoastic analysis usually require data that is not available. The utility of the results from these methodologies is minimal.

(7) Product Recovery -- Future remedial action design should be required to explore the possibility of recovering and utilizing the ground water pollutants. This has been widely practiced in cases involving hydrocarbon leakage from storage tanks. There may exist other instances in which the pollutants may be economically recovered, especially those involving spills. Recovery and utilization of the pollutants could help to defray costs of remedial measures.

SECTION IV

GROUND WATER POLLUTION CONTROL

The most important information required for any aquifer restoration study is related to the technical options available for ground water pollution control. In other words, what, if anything, can be done to prevent, abate or clean-up polluted ground water. Presented in this section is information on institutional measures and source control strategies for preventing/minimizing the occurrence of ground water pollution. The major section of this chapter addresses physical control measures such as well and interceptor systems, surface capping and liners, and physical containment barriers such as sheet piling, grouting, and slurry walls.

INSTITUTIONAL MEASURES

Institutional measures are primarily useful as preventive measures. The measures enumerated herein will be most useful to those groups who are interested in protecting ground water resources. Institutional measures include regional ground water management districts, source control strategies, land zoning, effluent charges/credits, aquifer standards, and guidelines.

Regional Ground Water Management Districts

The establishment of a regional ground water management district could be useful in prevention of long term quality and quantity-threatening activities. Possible functions of such a group could include information dissemination and some regulatory enforcement.

Information dissemination could include such things as proper use of agricultural chemicals, waste disposal guidelines, and lists of reputable ground water professionals such as well drillers. Minimal enforcement capabilities could help prevent such threatening activities as overuse or abuse of chemicals, indiscriminant dumping, or overpumping of certain formations.

Source Control Strategies

Implementation of certain source control strategies can reduce the threat to ground water resources. Source control measures could include source reduction steps such as recycling or waste pretreatment prior to disposal. Another source control strategy would be optimum site selection, i.e. locating potential threatening activities in the least vulnerable areas. The next section of this chapter will provide more information on this subject.

Land Zoning

Related to optimum site selection would be the use of prudent land zoning. One such measure would be to disallow industrial or waste disposal activities in ground water recharge areas.

Effluent Charges/Credits

One means of protecting ground water resources is by using economics as an incentive. By applying charges to effluents applied to or disposed on the soil, one can indirectly improve the quality of effluent from certain facilities. Credits can be applied to those facilities that move to improve the ground water resources such as those employing artificial recharge measures.

Aquifer Standards

A more authoritative institutional measure would be to establish ground water quality standards for aquifers. Beneficial use standards that are currently used for surface waters could be modified and applied to ground water resources.

Guidelines

Probably the most immediately effective measure would be to establish guidelines or standards for construction and operation of ground water-threatening activities. Many states are now adopting standards for construction of waste disposal facilities, and this could be expanded to include oil well drilling, mining and minerals extraction, on-site sewage disposal, and other activities.

SOURCE CONTROL STRATEGIES

Source control strategies represent attempts to minimize or prevent ground water pollution before a potential polluting activity is initiated. The objectives of source control strategies are to reduce the volume of waste to be handled, or reduce the threat a certain waste poses by altering its physical or chemical makeup.

Source control strategies are most applicable in the design of new facilities as a component of one or more ground water pollution prevention steps. However, some of the strategies can be used as abatement measures for existing facilities.

The development and design of each of the strategies listed below are site and situation specific; depending very heavily on the type of waste to be treated. Probably the only criteria universally applicable to these strategies is that they will require extensive monitoring and recordation. Most certainly, indiscriminate dumping must become a thing of the past. Some general advantages of source control strategies include:

(1) reduces the threat to the ground water environment;

(2) accelerates the time for "stabilization" of waste disposal facilities; and

(3) offers opportunities for economic recovery.

Two general disadvantages of source control strategies are:

(1) increased capital and maintenance costs; and

(2) monitoring and skilled operator requirements.

Table IV.1 lists some of the source control strategies that can be applied for ground water pollution prevention; usually at waste disposal facilities. The list is not totally comprehensive. It should be emphasized, however, that the possibility for implementation of source control strategies should be examined for all future waste disposal facilities. The following section contains additional information on stabilization and solidification strategies.

STABILIZATION/SOLIDIFICATION STRATEGIES

One means of reducing the threat to ground water from land disposal of waste materials is to structurally isolate the waste material in a solid matrix prior to landfilling. This process, known as stabilization/solidification, is becoming increasingly popular for

Table IV.1: Potential Source Control Strategies

I. Volume Reduction Strategies
  - A. Recycling
  - B. Resource Recovery
    - 1. materials recovery
    - 2. waste-to-energy conversion
  - C. Centrifugation
  - D. Filtration
  - E. Sand Drying Beds

II. Physical/Chemical Alteration Strategies
  - A. Chemical Fixation
    - 1. neutralization
    - 2. precipitation
    - 3. chelation
    - 4. cementation
    - 5. oxidation-reduction
    - 6. biodegradation
  - B. Detoxification
    - 1. thermal
    - 2. chemical -- ion-exchange, pyrolysis, etc.
    - 3. biological -- activated sludge, aerated lagoons, etc.
  - C. Degradation
    - 1. hydrolysis
    - 2. dechlorination

Table IV.1: (continued)

  3. photolysis
  4. oxidation

D. Encapsulation

E. Waste Segregation

F. Co-Disposal

G. Leachate Recirculation

hazardous and radioactive waste disposal (U.S. Environmental Protection Agency, 1979). The objective of solidification/stabilization processes is to chemically fix the waste in a solid matrix. This reduces the exposed surface area and minimizes leaching of toxic constituents. Effective immobilization includes reacting toxic components chemically to form compounds immobile in the environment and/or entrapping the toxic material in an inert stable solid. Thus stabilization and solidification have different meanings, although the terms are often used interchangeably. From a definitional perspective, stabilization refers to immobilization by chemical reaction or entrapping (watertight inert polymer or crystal lattice); while solidification means the production of a solid, monolithic mass with sufficient integrity to be easily transported. It will become apparent that these processes may overlap or take place within one operation. An example is cementation where the process both stabilizes by producing insoluble heavy metal compounds, and solidifies into a formed mass while entrapping the pollutants.

Chemical stabilization is designed to provide a substance which is more resistant to leaching, and also more amenable to the solidification process. By chemically fixing the hazardous waste constituents, their release will be minimized in the event of a breakdown of the solid matrix. Probably the simplest stabilization process is pH adjustment. In most industrial sludges, toxic metals are precipitated as amorphous hydroxides that are insoluble at an elevated pH. By carefully selecting a stabilization system of suitable pH, the solubility of any metal hydroxide can be minimized. Certain metals can also be stabilized by forming insoluble carbonates or sulfides. Care should be taken to ensure that these metals are not remobilized because of changes in pH or redox conditions after they have been introduced into the environment. Where possible, it is desirable to co-dispose of wastes which stabilize without the addition of extraneous chemicals.

Stabilized wastes can be solidified into a solid mass by microencapsulation or macroencapsulation. Microencapsulation refers to the dispersion and chemical reaction of the toxic materials within a solid matrix. Therefore, any breakdown of the solid material only exposes the material located at the surface to potential release to the environment. Macroencapsulation is the sealing of the waste in a thick, relatively impermeable coating layer. Plastic and asphalt coatings, or secured landfilling, are considered to be macroencapsulation methods. Breakdown of the protective layer with macroencapsulation could result in a significant release of toxic material to the environment.

Stabilization techniques have concentrated on the containment of toxic inorganic compounds. This is because many of the techniques originated as methods for treating radioactive wastes which consist primarily of inorganic isotopes. Also, organic compounds may interfere with the stabilization/solidification process, although small amounts may be incorporated under test conditions. Chemical oxidation or incineration have been found to be the most successful treatment methods for the majority of dangerous organic chemicals.

Stabilization/solidification processes should produce a material whose physical placement will not render the land on which it is disposed unusable for other purposes. The resultant stabilized/solidified material should be impervious, with good dimensional stability and [redacted] characteristics. It should also have satisfactory wet-dry and freeze-thaw weathering resistance. These properties plus optimum size and shape will make the material easily transportable under Department of Transportation (DOT) regulations, when compared with the precautions necessary when shipping wet wastes or sludges.

The nature of most stabilized industrial wastes precludes their use on agricultural land. However, they could be suitable for building subfoundations or as subgrade materials under roads or runways. For waste products expected to be scarce in the future (chromium, nickel, and manganese), it may be desirable to make them reclaimable. There is no optimum stabilization/solidification process applicable to every type of hazardous waste. Each individual waste must be characterized and bench tests and pilot studies performed to determine the suitability of a given process.

Present solidification/stabilization systems can be grouped into seven classes or processes:

(1) solidification through cement addition;

(2) solidification through the addition of lime and other pozzolanic materials;

(3) techniques involving embedding wastes in thermoplastic materials such as bitumen, parafin, or polyethylene;

(4) solidification by addition of an organic polymer;

(5) encapsulation of wastes in an inert coating;

(6) treatment of the wastes to produce a cementitious product with major additions of other constituents; and

(7) formation of a glass by fusion of wastes with silica.

WELL SYSTEMS

Well systems for ground water pollution control are based on manipulating the subsurface hydraulic gradient through injection or withdrawal of water. Well systems are designed to control the movement of the water phase directly, and subsurface pollutants indirectly. This approach is often referred to as plume management. There are three general classes of well systems. Two of these systems, which involve withdrawal of water, are well point systems and deep well systems. The other technology involves injection of water and can be referred to as a pressure ridge system. All three of the systems may require the installation of several wells at selected sites. These wells are then pumped (or injected) at specified rates so as to dictate the movement of the water phase and associated pollutants.

Construction

The single most important construction aspect of well systems is the installation of the wells. The sequence for installation of wells involves the following steps:

(1) setting up the drilling equipment;

(2) drilling the well hole;

(3) installing casings and liners;

(4) grouting and sealing the annular spaces between casings and boreholes;

(5) installing well screens and fittings;

(6) gravel-packing and placing materials; and

(7) developing the well.

Not all of the above steps are required for each well. Conversely, in addition to the above steps, the process could also require construction of above-ground facilities (pumphouses, etc.) and testing (pump tests).

Several methods exist for the initial drilling of the borehole, and these methods can usually be listed under one of the headings shown in Table IV.2. After the borehole is drilled, the next series of steps involves setting of casings, grouting and sealing of casings, and installing well screens. Excellent discussions are available on these procedures (Campbell and Lehr, 1977; and Johnson Division, UOP Inc., 1975).

The next step in well installation is well development or completion. Development is the process by which the finer particles of the water-bearing formation around the well are removed, thus resulting in enlarged passages for moisture travel. Three beneficial results of well development are:

(1) correction of damage to, or clogging of, water-bearing formation which occurs as a side effect from drilling;

(2) increases the porosity and permeability of the formation in vicinity of the well; and

(3) stabilizes the sand formation around a screened well so that the well will yield water free of sand (Johnson Division, UOP Inc., 1975).

The final activity would be the construction of the above-ground facilities associated with the well. This could include pumphouses, pumps and piping networks.

Table IV.2: Water Well Drilling Methods

Equipment Type	Procedure Description
1. Cable Tool	The cable tool drills by lifting and dropping a string of tools suspended on a cable. A bit at the bottom of the tool string strikes the bottom of the hole, crushing and breaking the formation material. Cuttings are removed by bailing or recirculation of a slurry. Casing is usually driven concurrent with drilling operations (Campbell and Lehr, 1977).
2. Hydraulic Rotary Drilling	Hydraulic rotary drilling consists of cutting a borehole by means of a rotating bit and removing the cuttings by continuous circulation of a drilling fluid as the bit penetrates the formation materials (Johnson Division, UOP Inc., 1975). Drilling fluid is usually a water-based slurry containing some fine material (clay) in suspension.
3. Reverse Circulation Drilling	Same as (2) except the fluid is forced downhole outside of the casing and returns up the inside of the casing. For (2) the route is down inside the casing and returning up outside the casing.
4. Air Rotary Drilling	Same as (2) only forced air becomes the drilling fluid.
5. Air-Percussion Rotary Drilling	Rotary technique in which the main source of energy for fracturing rock is obtained from a percussion machine connected directly to the bit.
6. Hollow-Rod Drilling	Similar to (1) except with more rapid and shorter strokes. Ball and check valve on bit allows water and cuttings to enter and travel up the casing (hollow-rod).
7. Jet Drilling	Similar to (6) except water is pumped down inside casing (hollow-rod) and returns up outside the casing.
8. Driven Wells	Pipe with a driving plug on the end is driven into the ground by repeated blows from a driving weight.
9. Hollow Stem Auger Drilling	Wells can be drilled in unconsolidated material and sampled by coring, with no drilling fluid or air required. Limited to shallow (less than 100 ft) unconsolidated material.

Design

The design of any of the three well systems should be preceded by a preliminary investigation. This preliminary investigation should involve a hydrogeologic study of the area. The hydrogeologic study should generate two categories of information. First, the contaminant plume dimensions (width, length, depth and general shape) and the hydraulic gradient across the plume should be determined (Lundy and Mahan, 1982). Second, the hydrogeologic characteristics of the aquifer should be identified. This information can be used along with the concepts of well hydraulics to establish the number and spacing of needed wells.

Some equations available for analyzing the flow to wells under different aquifer conditions are given in Tables IV.3 and IV.4 (Cohen and Miller, 1983). Table IV.5 summarizes the methods that can be used to calculate the radius of influence under various aquifer conditions (Kufs, et al., 1983). Simplistically, the design of a well system involves an iterative procedure of utilizing a set pumping rate, calculating the radius of influence associated with that rate and checking the radius of influence against the plume dimensions.

Lundy and Mahan (1982) identify three constraints which well recovery systems must satisfy:

(1) the recovery system must be located near enough to the downgradient plume boundary to reverse the hydraulic gradient at that boundary;

(2) total discharge is large enough to create limiting flowlines that bound the plume up to its widest part upgradient of the well system; and

Table IV.3: Analytical Solutions of Steady Flow Applicable to Corrective Actions (Cohen and Miller, 1983)

Equation	Assumptions
Steady flow from a line source to a line sink in a confined aquifer with no recharge	1. line source and sink are fully penetrating 2. no recharge occurs to confined aquifer 3. isotropic and homogeneous 4. horizontal flow 5. aquifer thickness varies linearly with x
Steady flow in an unconfined aquifer bounded by fully penetrating drains ($h_O=h_L$) with recharge	1. D-F assumptions 2. isotropic and homogeneous 3. constant and uniform infiltration rate 4. horizontal impermeable base 5. fully penetrating drains with equal head
Steady flow in an unconfined aquifer bounded by drains with recharge	1. D-F assumptions 2. isotropic and homogeneous 3. constant and uniform infiltration rate 4. horizontal impermeable base
Potential theory model of steady flow to drains in an unconfined aquifer with recharge	1. isotropic and homogeneous 2. constant and uniform infiltration rate 3. horizontal impermeable base
USEPA steady state landfill drainage model for horizontal liners or covers	1. D-F assumptions 2. isotropic and homogeneous 3. constant and uniform infiltration rate 4. horizontal impermeable base 5. drain at the impermeable base
USEPA steady state landfill drainage model for sloping liners or covers	1. D-F assumptions 2. isotropic and homogeneous 3. constant and uniform infiltration rate 4. sloping impermeable base
Steady state model for leachate collection with a sloping liner	1. isotropic and homogeneous 2. constant and uniform infiltration rate 3. impermeable base
Kirkham's 1967 D-F model of steady flow to drains in an unconfined aquifer with recharge	1. D-F assumptions 2. isotropic and homogeneous 3. constant and uniform infiltration rate 4. horizontal impermeable base 5. fully penetrating ditches

Table IV.3: (continued)

Equation	Assumptions
Hooghoudt's 1940 steady state drain spacing formula for an unconfined aquifer with recharge	1. D-F assumptions 2. isotropic and homogeneous 3. constant and uniform infiltration rate 4. horizontal impermeable base 5. drains at equal depth
Hooghoudt's steady state drain spacing equation for a two layer unconfined aquifer	1. D-F assumptions 2. constant and uniform infiltration rate 3. horizontal impermeable base 4. drains fully penetrate upper layer
Youngs' steady state inequality drain spacing model	1. isotropic and homogeneous 2. constant and uniform infiltration rate 3. horizontal impermeable base
Bouwer's model of steady flow to a drain in an unconfined aquifer with zoned recharge	1. D-F assumption 2. isotropic and homogeneous 3. constant and uniform infiltration rate in the recharge zone 4. horizontal impermeable base
Steady flow to a fully penetrating drain in a leaky and infinite confined aquifer	1. isotropic and homogeneous in each layer 2. leaky confined aquifer with horizontal flow 3. before pumping, the initial artesian and phreatic water levels are horizontal and coincident at h_i 4. during pumping, the phreatic water level is assumed to remain constant at h_i
Steady flow to a fully penetrating drain in a leaky and infinite two layered confined system	1. isotropic and homogeneous in each layer 2. leaky confined aquifer with horizontal flow 3. before pumping, the initial artesian and phreatic water levels are horizontal and coincident at h_i 4. during pumping, only the phreatic water level is assumed to remain horizontal at h_i 5. drain fully penetrates upper confined aquifer and is of great length

Table IV.3: (continued)

Equation	Assumptions
Steady flow to a fully penetrating drain in an infinite leaky unconfined aquifer	1. D-F assumptions 2. isotropic and homogeneous in each layer 3. constant and uniform infiltration rate 4. drain fully penetrates unconfined aquifer 5. artesian water level is horizontal or varies linearly with distance; it remains constant despite changes in the phreatic water level
Steady flow to partially penetrating drains in a leaky unconfined aquifer	1. D-F assumptions 2. isotropic and homogeneous in each layer 3. constant and uniform infiltration rate 4. artesian water level remains constant 5. horizontal impermeable base
Steady flow to a fully penetrating drain in a leaky confined-unconfined aquifer system	1. horizontal flow in both aquifers 2. isotropic and homogeneous in each layer 3. constant and uniform infiltration rate 4. horizontal impermeable base to the confined aquifer

Table IV.4: Analytical Solutions of Transient Flow Applicable to Corrective Actions (Cohen and Miller, 1983)

Equation	Assumptions
Transient flow to a fully penetrating drain in a semi-infinite aquifer caused by a unit step change in head	1. D-F assumptions if unconfined 2. isotropic and homogeneous 3. no infiltration 4. horizontal impermeable base 5. instantaneous head change at x=0 6. storage and transmissive properties constant with time 7. fully penetrating drain
Transient flow to a fully penetrating drain with constant discharge in a semi-infinite aquifer	1. D-F assumptions if unconfined 2. isotropic and homogeneous 3. no infiltration 4. horizontal impermeable base 5. constant discharge from drain 6. fully penetrating drain 7. storage and transmissive properties constant with time
Transient flow to a fully penetrating drain in a finite aquifer caused by a unit step change in head	1. D-F assumptions if unconfined 3. isotropic and homogeneous 3. no infiltration 4. horizontal impermeable base 5. storage and transmissive properties constant with time 6. instantaneous head change at fully penetrating drain 7. finite aquifer or parallel drain at 2L
Transient flow to a fully penetrating drain in a semi-infinite confined aquifer caused by a unit step change in head	1. isotropic and homogeneous confined aquifer 2. no infiltration or leakage 3. instantaneous head change at fully penetrating drain 4. horizontal impermeable base
Transient flow to a fully penetrating drain with constant discharge in a semi-infinite confined aquifer	1. isotropic and homogeneous confined aquifer 2. no infiltration or leakage 3. constant discharge from fully penetrating drain

Table IV.4: (continued)

Equation	Assumptions
Transient flow to a fully penetrating drain in an unconfined aquifer above a leaky confined aquifer	1. D-F assumptions for the unconfined aquifer 2. isotropic and homogeneous in each layer 3. no infiltration 4. water level of leaky confined aquifer is horizontal and constant with time and is coincident with the initial phreatic water level 5. storage and transmissive properties are constant with time
Glover's model of transient flow to partially penetrating parallel drains in an unconfined aquifer	1. D-F assumptions 2. isotropic and homogeneous 3. no infiltration 4. horizontal impermeable base 5. drains at equal elevation 6. storage and transmissive properties are constant with time
Brook's modification of Glover's transient flow model	1. D-F assumptions 2. isotropic and homogeneous 3. no infiltration 4. horizontal impermeable base 5. drains at equal elevation
Dumm, Tapp and Moody's model of transient flow to partially penetrating drains in an unconfined aquifer	1. D-F assumptions 2. isotropic and homogeneous 3. no infiltration 4. horizontal impermeable base 5. drains at the same elevation 6. initial water level configuration is a parabola
Maasland's model of transient flow to partially penetrating drains in an unconfined aquifer with recharge	1. D-F assumptions 2. isotropic and uniform infiltration rate 3. horizontal impermeable base 4. drains at the same elevation 5. storage and transmissive properties are constant with time
Kirkham's potential theory model of transient flow to partially penetrating drains in an unconfined aquifer with recharge	1. isotropic and homogeneous 2. constant and uniform infiltration rate 3. horizontal impermeable base 4. storage and transmissive properties are constant with time 5. initial phreatic water level taken as the equilibrium condition during steady state

Table IV.4: (continued)

Equation	Assumptions
Terzidis' drain spacing model for transient flow to partially penetrating drains in an unconfined aquifer	1. D-F assumptions 2. isotropic and homogeneous 3. no infiltration 4. horizontal impermeable base 5. storage and transmissive properties are constant with time 6. initial water table is horizontal
Van Schilfgaarde's D-F drain spacing equation for transient flow to partially penetrating drains in an unconfined aquifer	1. D-F assumptions 2. isotropic and homogeneous 3. no infiltration 4. horizontal impermeable base 5. storage and transmissive properties are constant with time 6. initial water table is an ellipse
Van Schilfgaarde's D-F drain spacing equation for transient flow to fully penetrating drains in an unconfined aquifer	1. D-F assumptions 2. isotropic and homogeneous 3. no infiltration 4. horizontal impermeable base 5. fully penetrating drains 6. initial water table is an ellipse 7. storage and transmissive properties constant with time
Transient flow to fully penetrating drains in a sloping unconfined aquifer with no recharge	1. D-F assumption 2. isotropic and homogeneous 3. no infiltration 4. sloping impermeable base 5. initial water table parallel to the sloping base 6. storage and transmissive properties are constant with time 7. vertical seepage faces are located at each drain
Hantush's 1967 D-F model of the growth and decay of water table mounds in response to uniform percolation	1. D-F assumptions 2. isotropic and homogeneous 3. infinite in areal extent 4. horizontal impermeable base 5. rectangular recharge area receiving constant and uniform infiltration 6. storage and transmissive properties remain constant with time

Table IV.5: Methods for Calculating Radius of Influence (Kufs, et al., 1983)

Pumping Condition	Method
Equilibrium	
- Exact	$\ln R_o = \frac{K(H^2-hw^2)}{458\ Q} + \ln R_o = \frac{T(H-hw)}{229\ Q} + \ln r_w$
- Approximate	$R_o = 3(H-h_w)\ (0.47K)^{\frac{1}{2}}$
Non-Equilibrium	
- Exact	Drawdown vs. log distance plots
- Approximate	$R_o = r_w + (\frac{Tt}{4790\ S})^{\frac{1}{2}}$

R_o = radius of influence (ft)

K = permeability (gpd/ft^2)

H = total head (ft)

h_w = head in well (ft)

Q = pumping rate (gpm)

r_w = well radius (ft)

T = transmissivity (gpd/ft)

t = time (min)

S = storage coefficient (dimensionless)

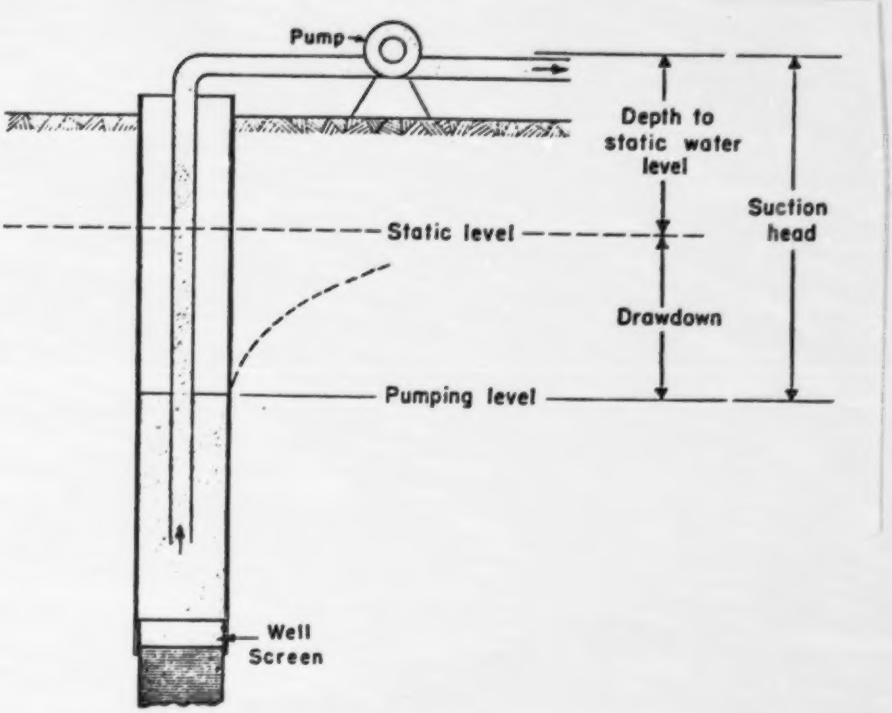
(3) drawdowns of water levels resulting from withdrawals from the system do not exceed limits that are a function of aquifer saturated thickness.

Well point systems involve a number of closely-spaced, shallow wells each connected to a main pipe (header) which is connected to a centrally-located suction lift pump. Well point systems are used only for shallow, water table aquifers because the maximum drawdown obtainable by suction lift is the difference between the suction limit of the pump and the distance from the static water level to the center of the pump. The upper limit for lifting water by suction lift is around 25 feet. Pumping by suction lift is depicted in Figure IV.1 (Johnson Division, UOP Inc., 1975). Well point systems should be designed so that the radius of influence (drawdown) of the system completely intercepts the plume of contaminants as shown in Figure IV.2.

Deep well systems are similar to well point systems except they are used for greater depths and are usually pumped individually. Once again, the deep well system should be designed so that its radius of influence completely intercepts the contaminant plume as shown in Figure IV.2.

Pressure ridge systems can be conceptualized as the inverse of the previous two systems. Pressure ridges use the injection of water to form an upconing of the water table which acts as a barrier to ground water flow. Figure IV.3 depicts the phenomena of a pressure ridge system. These systems have found their widest application in coastal areas to prevent saltwater intrusion.

The basis of design for all three of the well systems is that movement of the ground water flow and pollutant be completely


Pump
Depth to static water level
Suction head
Static level
Drawdown
Pumping level
Well Screen

Note: When pumping wells by suction lift, the maximum drawdown obtainable is the difference between the suction limit of the pump and the distance from the static water level to the center of the pump.

Figure IV.1: Pumping by Suction Lift (Johnson Division, UOP Inc., 1975).

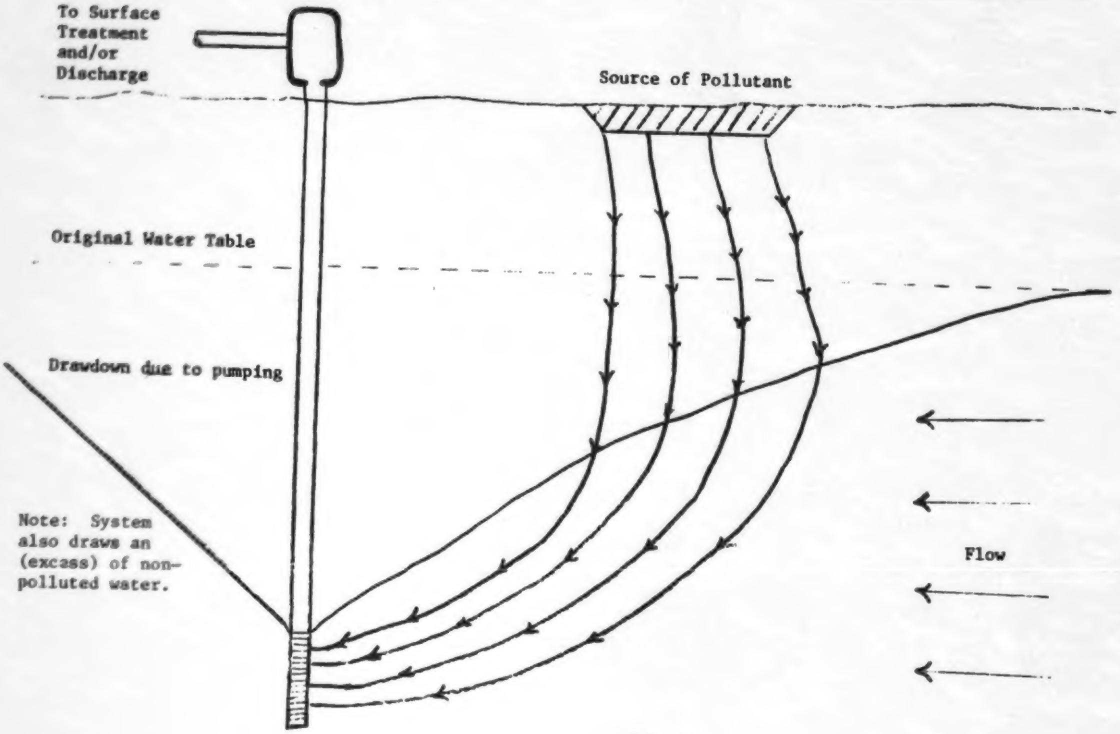

To Surface Treatment and/or Discharge
Source of Pollutant
Original Water Table
Drawdown due to pumping
Note: System also draws an (excess) of non-polluted water.
Flow

Figure IV.2: Principle of Withdrawal Wells

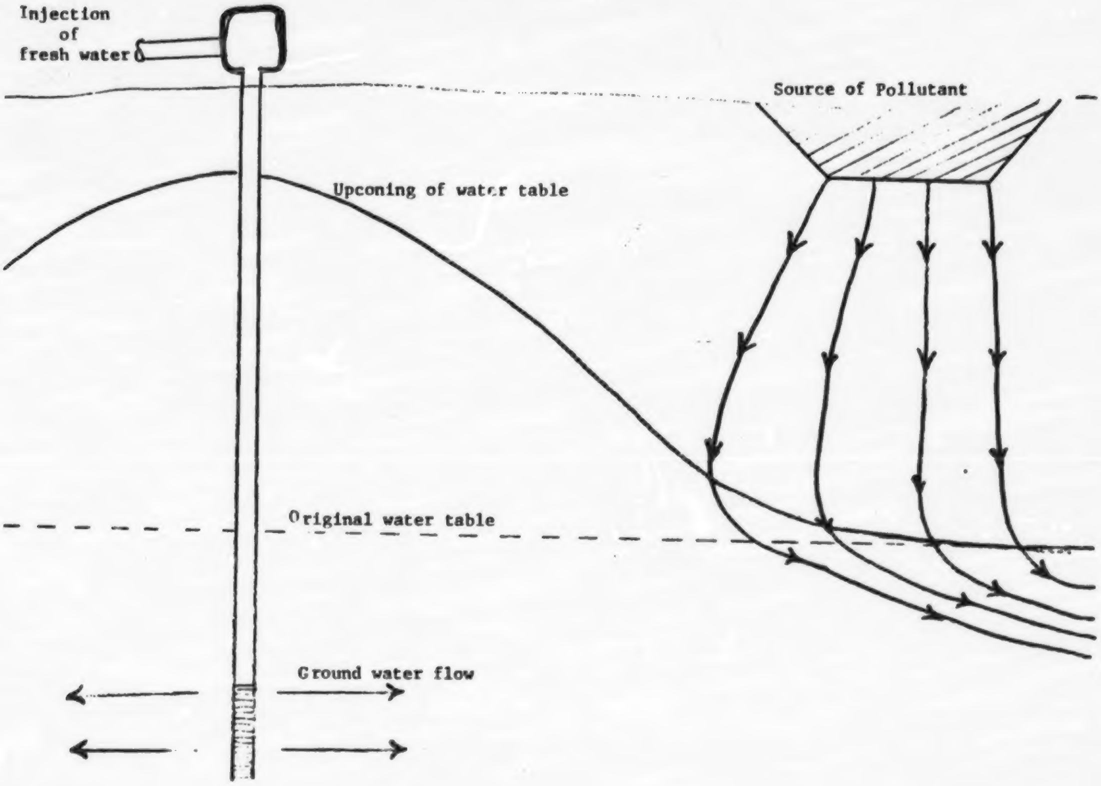

Injection of fresh water
Source of Pollutant
Upconing of water table
Original water table
Ground water flow

Figure IV.3: Principles of Pressure Ridge System

controlled. Through the use of data obtained from the initial hydrogeologic study, and the principles of well hydraulics, the number, depth, spacing, and pumping or injection rate of the wells can be specified. In addition, estimates of the time required for the remedial actions can be made.

Application in Hydrocarbon Recovery

The discussion of the three types of well systems above has been general so as to be applicable to a wide variety of situations. However, there is one situation in which the purpose of the well system is very specific. That situation is when the contaminant is not water soluble and tends to float on top of the water table; this most often involves hydrocarbons. A unique aspect of this type of problem is that the contaminant provides a strong economic incentive for ground water cleanup since the product recovered from the water table can be utilized. Because of this economic incentive and the large number of instances of hydrocarbon leakage from storage tanks, considerable work has been directed toward developing hydrocarbon recovery systems.

Blake and Lewis (1982) have outlined four design options available for hydrocarbon recovery systems: (1) single pump systems utilizing one recovery well; (2) single-pump systems utilizing multiple wells; (3) two-pump systems utilizing two recovery wells; and (4) two-pump systems utilizing one recovery well. The single-pump, single well system is depicted in Figure IV.4. The advantages of this system include low equipment and drilling costs. However, this system produces an oil-water mix requiring separation of the surface. One-pump systems

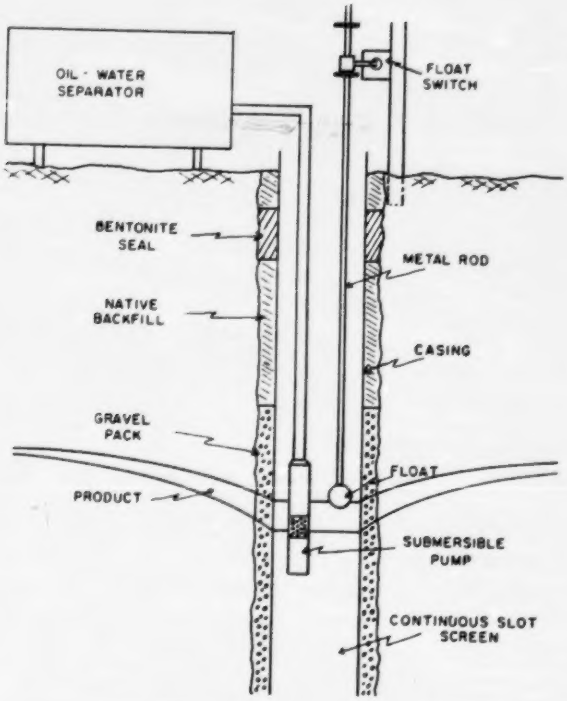

OIL - WATER SEPARATOR
FLOAT SWITCH
BENTONITE SEAL
METAL ROD
NATIVE BACKFILL
CASING
GRAVEL PACK
FLOAT
PRODUCT
SUBMERSIBLE PUMP
CONTINUOUS SLOT SCREEN

Figure IV.4: Schematic of One Pump System Utilizing a Submersible Pump and Float Controls (Blake and Lewis, 1982).

utilizing multiple well points are plagued by the same problems as the single-well arrangements, but they may be the most feasible option in low permeability formations (Blake and Lewis, 1982).

The two-pump, two-well system is depicted in Figure IV.5. The deeper well serves the purpose of producing a gradient toward the shallower (product recovery) well. The advantage of this system is the ability to keep the product and the produced water separate; one disadvantage is the increased cost of multiple wells. Additionally, this type of system can require fairly sophisticated surface monitoring equipment to insure proper operation.

The most desirable product recovery system is that involving two pumps in one well as depicted in Figure IV.6. The basis of this system is similar to the previous system, i.e., the lower pump produces a gradient toward the well and the upper pump removes the accumulated product. This system separates the product from the produced water, but only involves a single well. This system can also be fully automated. The disadvantages of this system include: the increased well diameter to house two pumps; expensive operational monitoring equipment; the system requires careful start up operations and calibration; and the requirements for frequent inspections.

Costs

The total cost of a well system is dominated by two individual cost items: 1) the cost of the installation, and 2) operation and maintenance costs. In this time of rising energy costs, the power required to pump the well system will probably be the single most

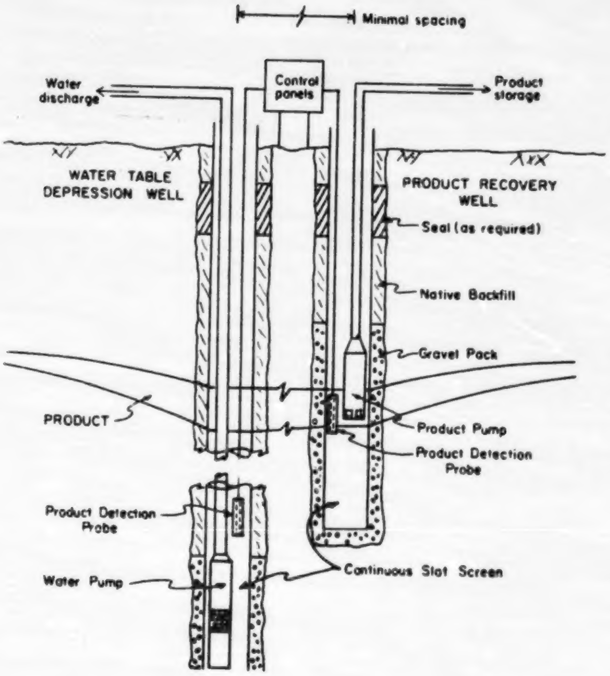

Minimal spacing
Water discharge
Control panels
Product storage
WATER TABLE DEPRESSION WELL
PRODUCT RECOVERY WELL
Seal (as required)
Native Backfill
Gravel Pack
PRODUCT
Product Pump
Product Detection Probe
Product Detection Probe
Water Pump
Continuous Slot Screen

Figure IV.5: Schematic of Two Pump System Utilizing Two Small Diameter Wells (Blake and Lewis, 1982).

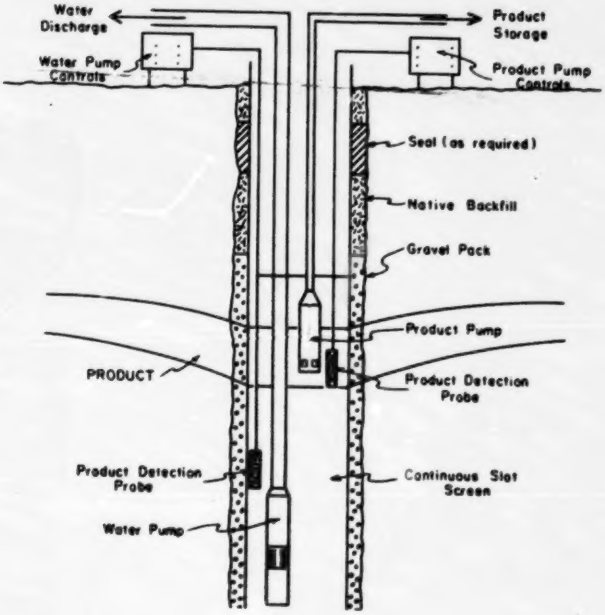

Water Discharge
Water Pump Controls
Product Storage
Product Pump Controls
Seal (as required)
Native Backfill
Gravel Pack
Product Pump
PRODUCT
Product Detection Probe
Product Detection Probe
Continuous Slot Screen
Water Pump

Figure IV.6: Schematic of Two Pump System Utilizing One Recovery Well (Blake and Lewis, 1982).

dominating cost factor. A cost analysis study for a variety of well systems was conducted by Gibb (1971) and included in Campbell and Lehr (1977). The actual cost figures are somewhat dated, but the principles employed would be applicable today. A schematic of a well completed in unconsolidated sediments (sand and gravel) is shown in Figure IV.7, with corresponding cost relationships shown in Figure IV.8. Similar information for a gravel-packed well in consolidated to partly consolidated sediments (sand and gravel) is shown in Figures IV.9 and IV.10; for a shallow well in consolidated sediments (sandstone, limestone, or dolomite) in Figures IV.11 and IV.12; and for a deep well in consolidated sediments in Figures IV.13 and IV.14 (Campbell and Lehr, 1977).

Advantages and Disadvantages

The use of well systems is presently, and probably will continue to be, the most utilized method of ground water pollution control. This is not without good reason. Well systems represent the most assured means of controlling subsurface flows contaminants. Engineers and hydrogeologists have a somewhat firmer understanding of the mechanics of well hydraulics than they do of some potential aquifer restoration strategies. However, well systems are not without their limitations. A comparison of some of the advantages and disadvantages of well systems is in Table IV.6.

INTERCEPTOR SYSTEMS

Interceptor systems involve excavation of a trench below the water table, and possibly the placement of a pipe in the trench. Subsurface

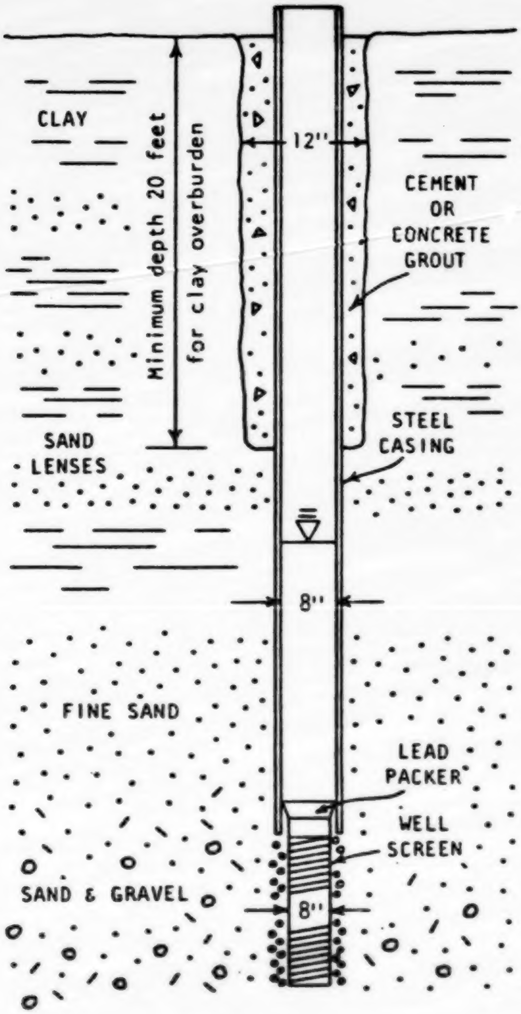

CLAY
Minimum depth 20 feet
for clay overburden
12"
CEMENT
OR
CONCRETE
GROUT
SAND
LENSES
STEEL
CASING
8"
FINE SAND
LEAD
PACKER
WELL
SCREEN
SAND & GRAVEL
8"

Figure IV.7: Well Completed in Unconsolidated Sediments (Sand and Gravel) (Campbell and Lehr, 1977).

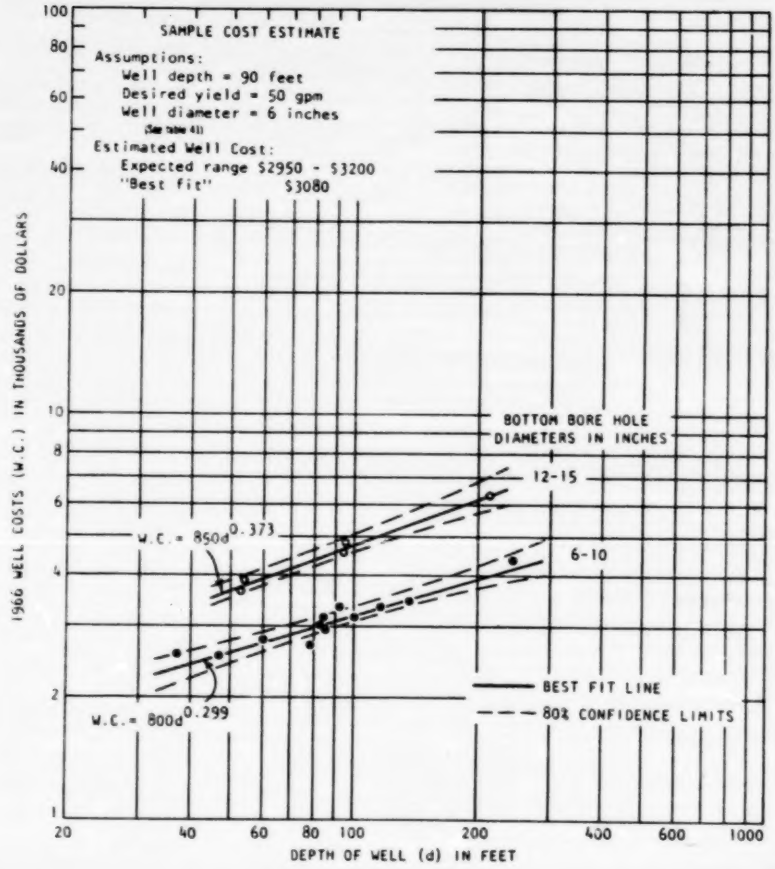


Figure IV.8: Cost of Cased Wells Finished in Sand and Gravel (Campbell and Lehr, 1977).

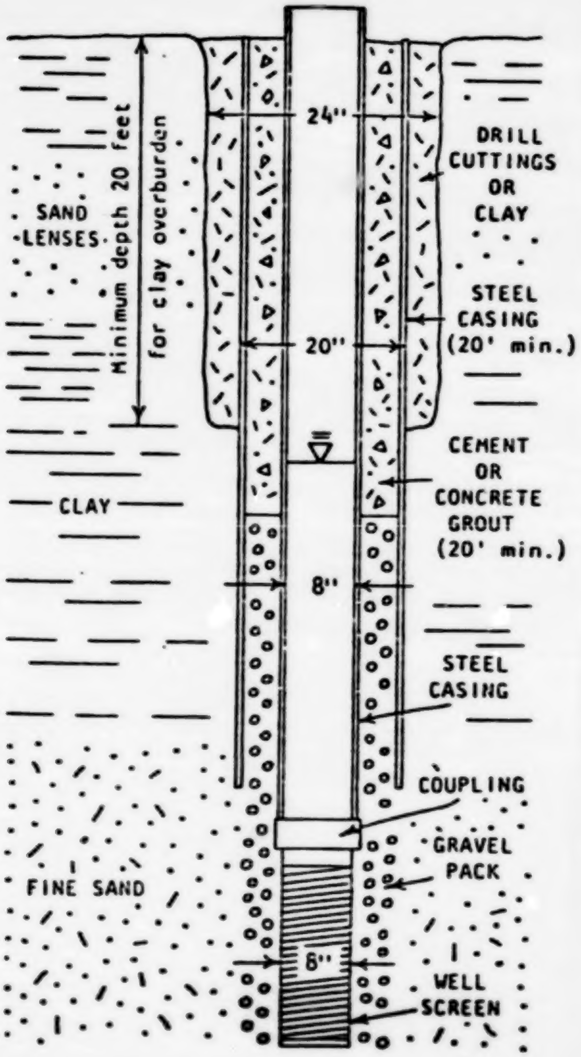

24"
DRILL CUTTINGS OR CLAY
SAND LENSES
Minimum depth 20 feet for clay overburden
STEEL CASING (20' min.)
20"
CEMENT OR CONCRETE GROUT (20' min.)
CLAY
8"
STEEL CASING
COUPLING
GRAVEL PACK
FINE SAND
8"
WELL SCREEN

Figure IV.9: Gravel-Packed Well Completed in Sand and Gravel - Unconsolidated to Partly Consolidated Sediments (Campbell and Lehr, 1977).

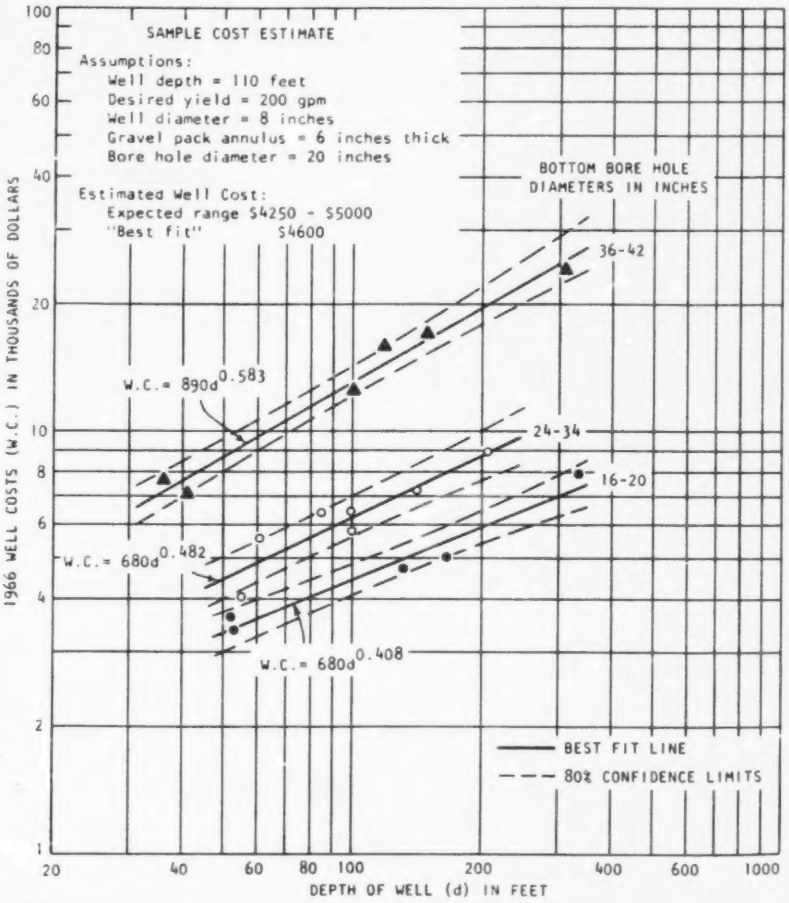


Figure IV.10: Cost of Gravel-Packed Wells Finished in Sand and Gravel (Campbell and Lehr, 1977).

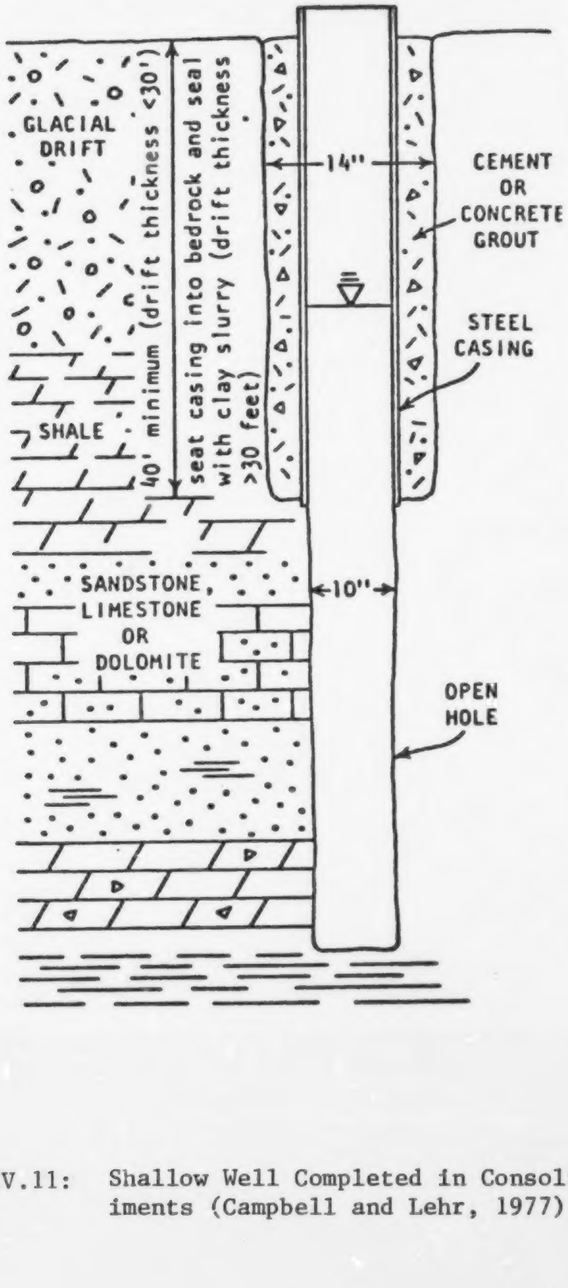

GLACIAL DRIFT
SHALE
40' minimum (drift thickness <30')
seat casing into bedrock and seal with clay slurry (drift thickness >30 feet)
14"
CEMENT OR CONCRETE GROUT
STEEL CASING
SANDSTONE, LIMESTONE OR DOLOMITE
10"
OPEN HOLE

Figure IV.11: Shallow Well Completed in Consolidated Sediments (Campbell and Lehr, 1977).

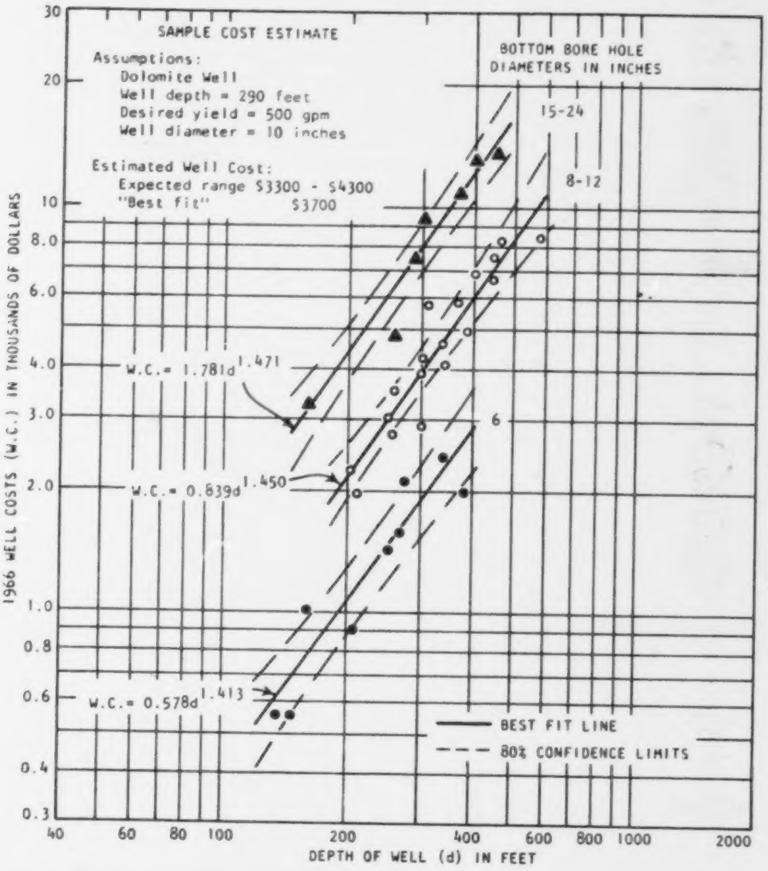


Figure IV.12: Cost of Shallow Sandstone, Limestone, or Dolomite Bedrock Wells (Campbell and Lehr, 1977).

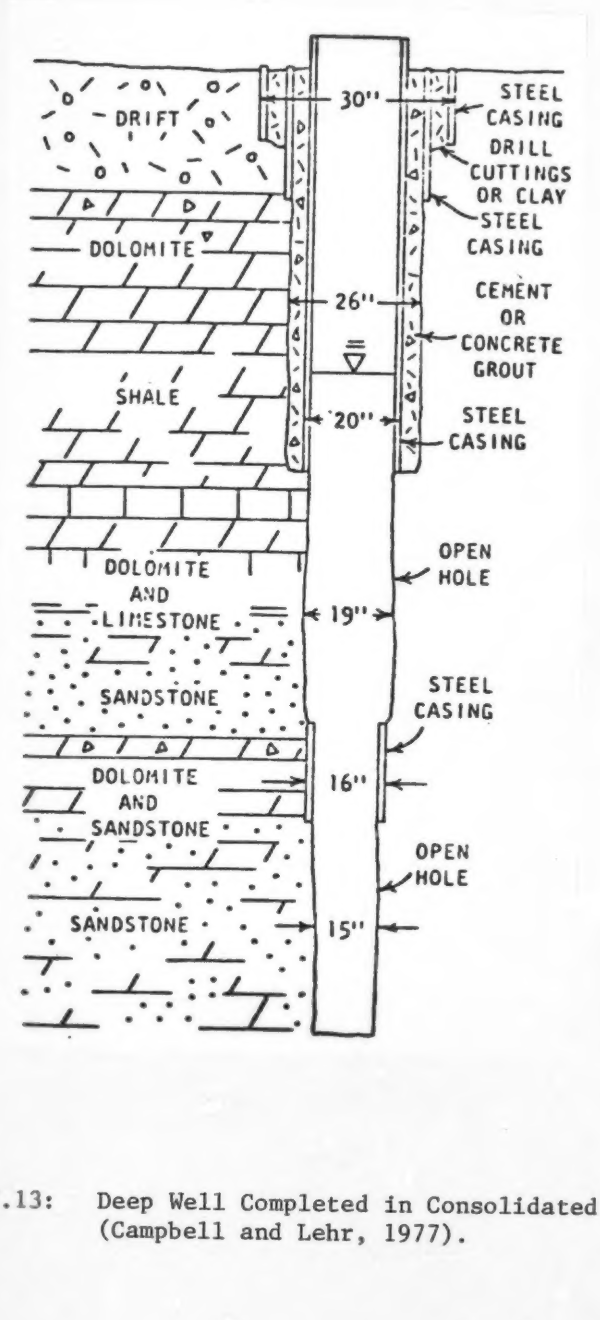

DRIFT
DOLOMITE
SHALE
DOLOMITE AND LIMESTONE
SANDSTONE
DOLOMITE AND SANDSTONE
SANDSTONE
30"
26"
20"
19"
16"
15"
STEEL CASING
DRILL CUTTINGS OR CLAY
STEEL CASING
CEMENT OR CONCRETE GROUT
STEEL CASING
OPEN HOLE
STEEL CASING
OPEN HOLE

Figure IV.13: Deep Well Completed in Consolidated Sediments (Campbell and Lehr, 1977).

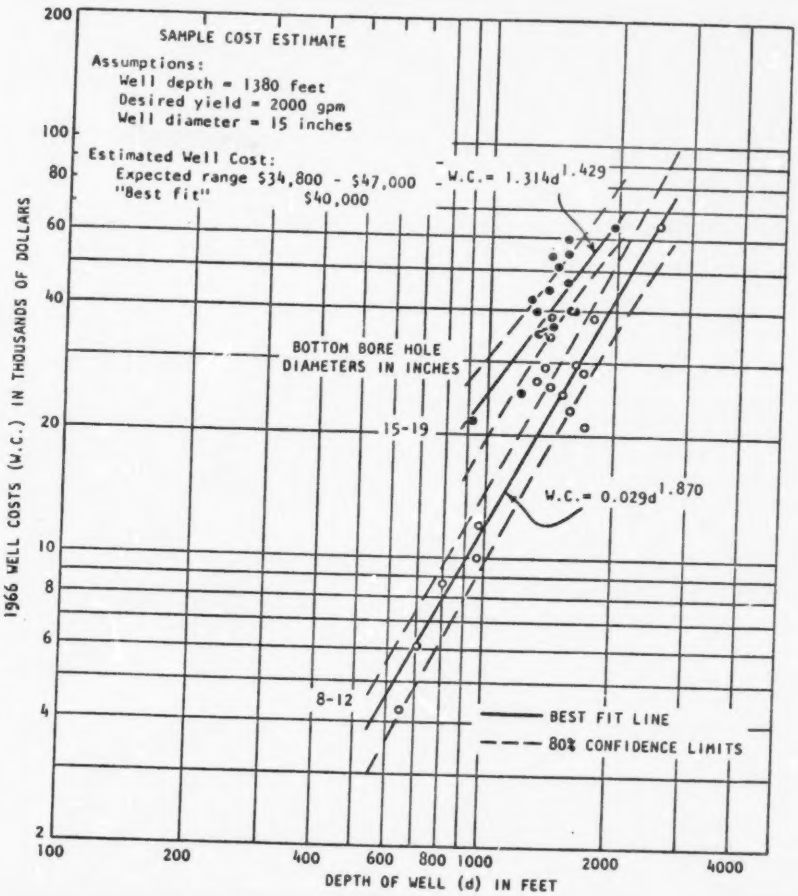


Figure IV.14: Cost of Deep Sandstone Wells (Campbell and Lehr, 1977).

Table IV.6: Advantages/Disadvantages of Well Systems

Advantages	Disadvantages
1. Efficient and effective means of assuring ground water pollution control.	1. Operation and maintenance costs are high.
2. Can be installed readily.	2. Require continued monitoring after installation.
3. Previously installed monitoring wells can sometimes be employed as part of well system.	3. Withdrawal systems necessarily remove clean (excess) water along with polluted water.
4. Can sometimes include recharge of aquifer as part of the strategy.	4. Some systems may require the use of sophisticated mathematical models to evaluate their effectiveness.
5. High design flexibility.	5. Withdrawal systems will usually require surface treatment prior to discharge.
6. Construction costs can be lower than artificial barriers.	6. Application to fine soils is limited.

drains or trenches function similarly to an infinite line of extraction wells, that is, they effect a continuous zone of depression which runs the length of the drainage trench (Kufs, et al., 1983). Figure IV.15 depicts an interceptor trench. Usually the trench receives perforated pipe and coarse backfill material for efficiency of collection and transport of incoming water. There are several names applied to interceptor systems; examples include their classification as preventive measures (leachate collection systems) or abatement measures (interceptor drains).

Construction

a. Collector Drains

Construction of interceptor systems is relatively simple and involves digging a system of trenches, placing perforated pipes in the trenches, and backfilling with a coarse material such as gravel. Usually collector systems will consist of a series of feeder pipes (laterals) flowing into a main collecting pipe (header) as shown in Figure IV.16. From the header, the collected water will flow to a sump where it is then pumped to the surface for treatment and/or discharge. Collector systems used in a preventive mode, such as a leachate collection system, usually include a series of 4 to 6 inch laterals draining into 8 to 12 inch headers, all arranged in either a herringbone or gridiron design as shown in Figure IV.17.

Interceptor systems used in an abatement mode can be classified as relief drains or interceptor drains. Relief drains are installed in areas where the hydraulic gradient is relatively flat. They are

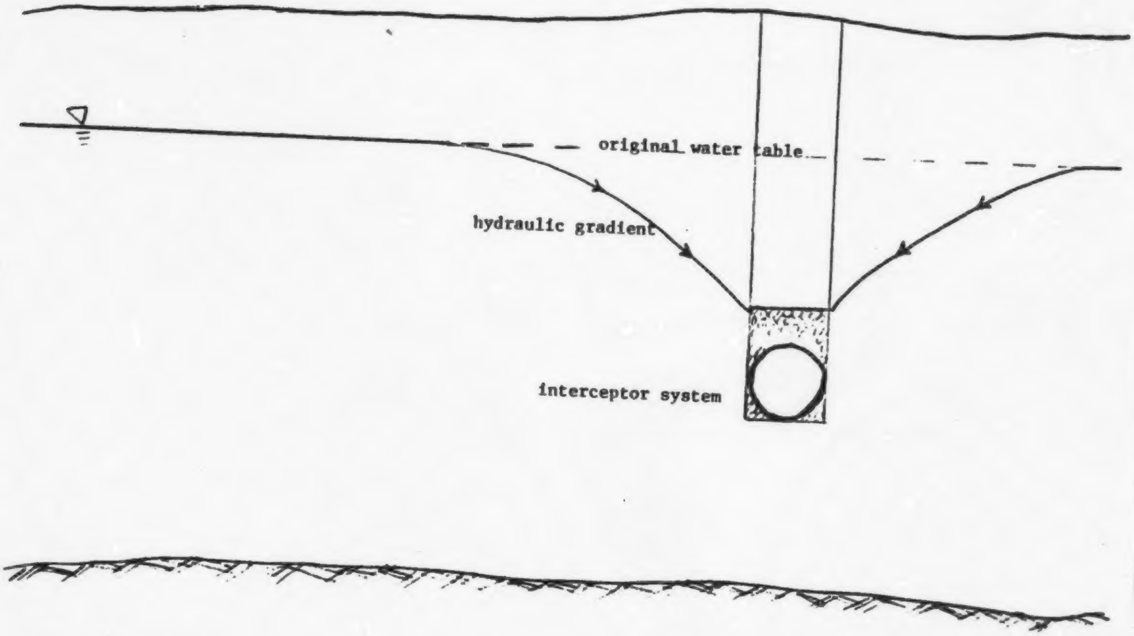
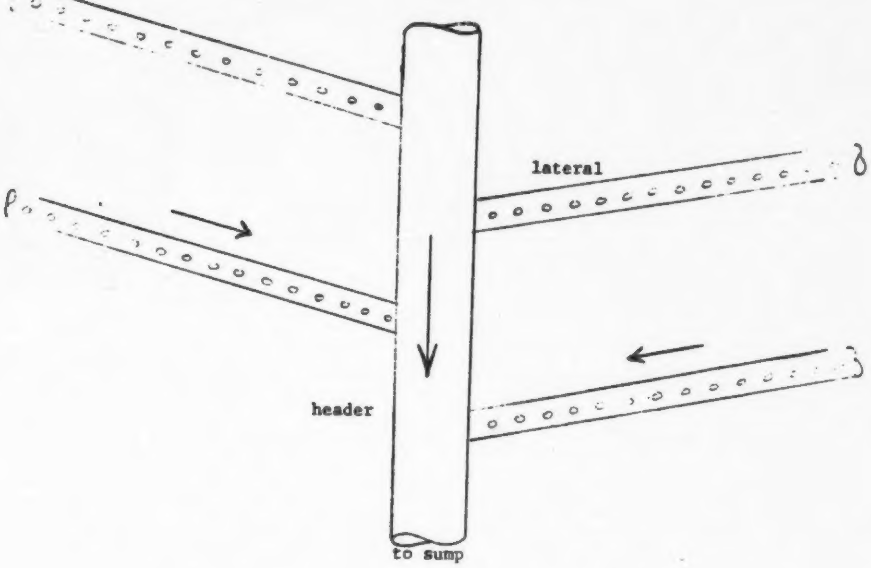
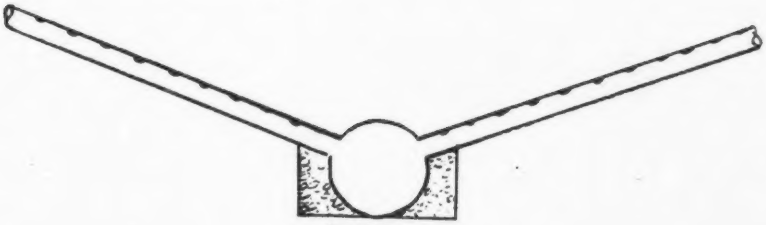

original water table
hydraulic gradient
interceptor system

Figure IV.15: Hydraulic Gradient Toward Interceptor System

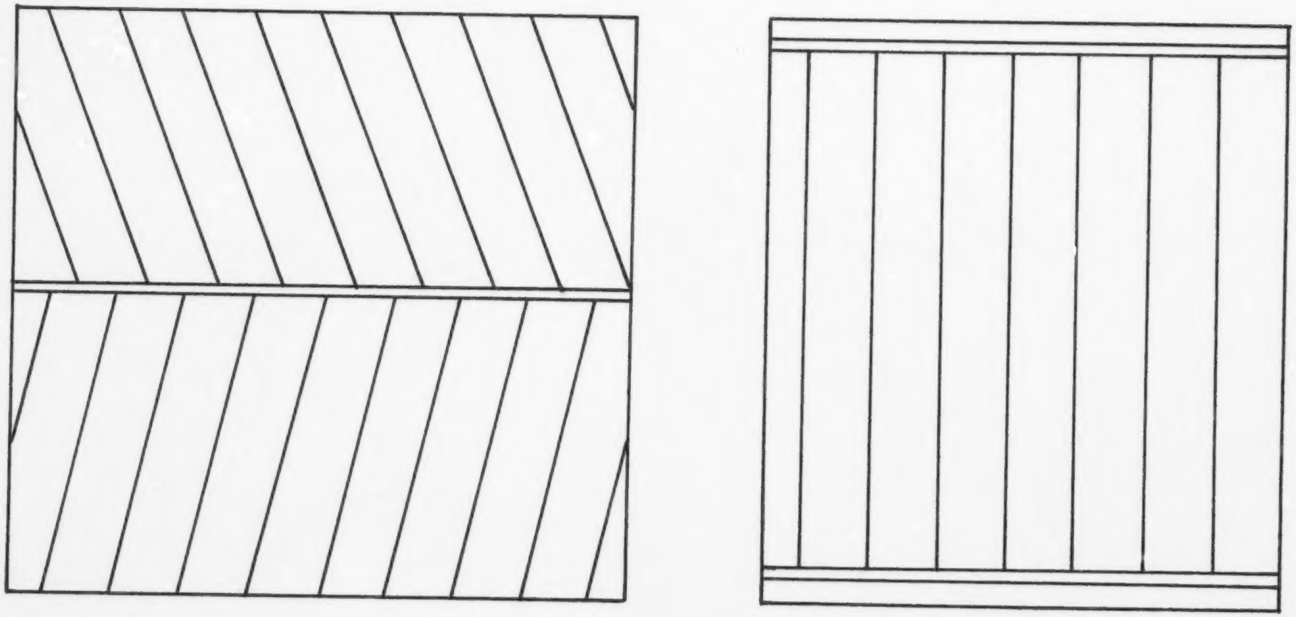

lateral
header
to sump

Plan



Profile

Figure IV.16: Collector Drain System



(a) Herringbone

(b) Gridiron

Figure IV.17: Collector System Layouts

generally used to lower the water table beneath a site, or to prevent contamination from reaching a deeper, underlying aquifer. Relief drains are installed in parallel on either side of the site such that their areas of influence overlap and contaminated ground water does not flow between the drain lines. They can also be installed completely around the perimeter of the site (Kufs, et al., 1983).

Interceptor drains are used to collect ground water from an upgradient source in order to prevent leachate from reaching wells and/or surface water located hydraulically downgradient from the site. They are installed perpendicular to ground water flow. A single interceptor drain located at the toe of the landfill, or two or more parallel interceptors may be needed, depending upon the circumstances (Kufs, et al., 1983).

b. Interceptor Trenches

Interceptor trenches can be either active (pumped) or passive (gravity flow). Active systems will have intermediately-spaced vertical removal wells or a perforated, horizontal removal pipe (collector drain) in the bottom of the trench. Active systems are usually backfilled with a coarse sand or gravel to promote wall stability. Passive systems are used almost exclusively for collection of pollutants that flow on the surface of water (e.g., oil and hydrocarbons). Passive systems are usually left open with the installation of a skimming pump for removal of the pollutant only.

All interceptor trenches require excavation to at least 3 or 4 feet below the water table to prevent the escape of inflowing pollutant and to speed up the inflow of further free pollutant (American Petroleum Institute, 1980). In active systems, the pumping capacity should be great enough to keep water drawn down to the bottom of the ditch. Additionally, pumping (active system) or skimming (passive system) must be continuous, or the collected pollutant will tend to seep into the trench walls and continue downgradient (American Petroleum Institute, 1980).

The main construction activity associated with interceptor trenches is excavation of the trench. This can be accomplished with conventional equipment. The trench width should be wide enough to accomodate pipes or pumps if needed, yet it should be kept narrow to minimize the amounts of soil removed. Active (pumped) systems will require greater depths, once again to accomodate pipes or pumps.

It has been suggested (American Petroleum Institute, 1972, 1980) that the downgradient wall of the trench be lined with an impermeable material such as polyethylene film to prevent floating pollutants from passing through the trench and continuing downgradient. However, Pastrovich, et al. (1979) indicates that the pollutant will tend to find its way around the ends of the barrier and penetrate the ground beyond while, at the same time, equalization of the hydrostatic pressure on both sides of the film tend to cause it to float away from the wall. As noted above, continuous removal of the pollutant and water from the trench will cause drawdown on both sides of the trench, thus preventing further migration of the pollutant.

After excavation of the trench, the passive system will usually require installation of a skimming pump. Active systems will require the installation of removal wells or collector drains, with subsequent backfilling of the trench with coarse sand or gravel.

Design

a. Collector Drains

The primary design parameters for a collector drain systems are (1) the size of the pipe; and (2) the spacing of the pipe. To determine the size of pipe required, the carrying capacity of the pipe is assumed to be equal to the design seepage, and the pipe velocity is described by Mannings equation. The resulting equation in a rearranged form is (Luthin, 1957):

$$d = 0.892\ (SC)^{0.375}\ (A)^{0.375}\ s^{-0.1875}$$

where

d = inside diameter of pipe (inches)

A = drainage area (acres)

SC = seepage coefficient (inches/day)

s = hydraulic gradient

For purposes of design of drain spacing, from the Dupuit-Fochheimer theory the ground water surface between two tile lines may be taken as a portion of an ellipse as shown in Figure IV.18 and described as follows (Spangler and Handy, 1973):

$$\frac{S^2}{(b^2 - a^2)} = \frac{4k}{R}$$

where

S = tile line spacing (meters)

a = depth to impermeable barrier under tile (meters)

b = depth to impermeable barrier halfway between tiles (meters)

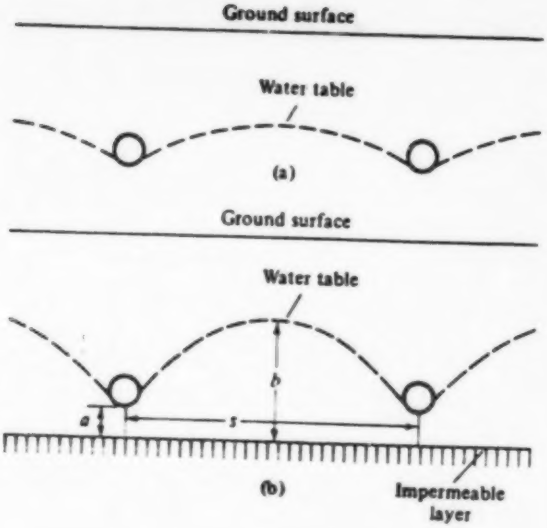

Ground surface
Water table
(a)
Ground surface
Water table
b
a
s
(b)
Impermeable layer

Figure IV.18: Shape of Water Table Adjacent to Tile Drains. (a) Relatively Permeable Soil; (b) Less Permeable Soil (Spangler and Handy, 1973).

k = hydraulic conductivity of soil (meters/day)

R = infiltrating rainfall (meters/day)

A wide variety of equations for parallel subsurface drains have been developed for varying aquifer conditions. These equations are outlined in Tables IV.3 and IV.4.

b. Interceptor Trenches

Design of interceptor trenches is different from that of relief drains. In order to decide where to position the trench to intercept the desired flow, the relationship between depth and flow, and the upgradient and downgradient influence of the trench must be known. The upgradient influence can be determined from the following (Kufs, et al., 1983):

$$D_u = 4/3 \ H \tan \phi$$

where

D_u = effective distance of drawdown upgradient (meters)

H = saturated thickness of the water-bearing strata not affected by drainage (meters)

ϕ = angle between the initial water table or ground surface and the horizontal plane.

The theoretical expression for the downgradient influence is as follows:

$$D_d = \frac{K \tan \phi}{q} (h_1 - h_2 + D_2)$$

where

D_d = distance downgradient from the drain where the water table is lowered to the desired depth (meters)

K = hydraulic conductivity (meters/day)

q = drainage coefficient (meters/day)

h_1 = effective depth of the drain (meters)

h_2 = desired depth to the water table after drainage (meters)

D_2 = distance from the ground surface to the water table before drainage at the distance D_d downgradient from the drain (meters)

Costs

Shallow drainage by trenches or collector drains has been estimated to cost on the order of \$1235 to \$1730 capital cost per hectare drained (\$500 to \$700 per acre), depending on the depth of placement and materials used. Labor and maintenance costs are about \$1500 per year (Tolman, et al., 1978).

Advantages and Disadvantages

Listed in Table IV.7 are some of the advantages and disadvantages particular to subsurface drains (interceptor systems). The most obvious advantage of interceptor systems is their relatively simple construction methods. Just as obvious is the disadvantage of requiring continuous monitoring and maintenance. Other advantages of interceptor systems are:

(1) not only easy but also inexpensive to install;

(2) useful for intercepting landfill side seepage and runoff (U.S. Environmental Protection Agency, 1982);

(3) useful for collecting leachate in poorly permeable soils (U.S. Environmental Protection Agency, 1982);

(4) large wetted perimeter allows for high rates of flow (U.S. Environmental Protection Agency, 1982);

(5) possible to monitor and recover pollutants; and

(6) produces much less fluid to be handled than well-point systems.

Table IV.7: Advantages/Disadvantages of Subsurface Drains (U.S. Environmental Protection Agency, 1982)

Advantages	Disadvantages
1. Operation costs are relatively cheap since flow to underdrains is by gravity.	1. Not well suited to poorly permeable soils.
2. Provides a means of collecting leachate without the use of impervious liners.	2. In most instances it will not be feasible to situate underdrains beneath an existing site.
3. Considerable flexibility is available for design of underdrains; spacing can be altered to some extent by adjusting depth or modifying envelope material.	3. System requires continuous and careful monitoring to assure adequate leachate collection.
4. Systems fairly reliable, providing there is continuous monitoring.	
5. Construction methods are simple.	

Disadvantages of interceptor systems include:

(1) when dissolved constituents are involved, it may be necessary to monitor ground water downgradient of the recovery line (Quince and Gardner, 1982);

(2) open systems require safety precautions to prevent fires or explosions;

(3) interceptor trenches are less efficient than well-point systems;

(4) operation and maintenance costs are high;

(5) not useful for deep disposal sites (U.S. Environmental Protection Agency, 1982); and

(6) may interfere with use of land.

SURFACE WATER CONTROL, CAPPING AND LINERS

Surface water control, capping and liners are three different technologies that are usually used in conjunction with each other. The three technologies serve different purposes in preventing ground water pollution. Surface water control measures are designed to minimize the amount of surface water flowing onto a site, thus reducing the amount of potential infiltration. Capping of a site is designed to minimize the infiltration of any surface water or direct precipitation that does come onto a site. Impermeable liners provide ground water protection by inhibiting downward flow of low quality leachate and/or attenuating pollutants by adsorption processes. These technologies are most often used as preventive measures, although surface water control and capping have also been used successfully to abate ground water pollution problems (Emrich, Beck and Tolman, no date). Technologies also exist for placement of liners after a polluting activity has been initiated;

these usually involve the use of grouts which are discussed in a subsequent section.

Surface water control measures represent a relatively inexpensive means of minimizing future ground water pollution problems, and as such, should be part of any current site design. Surface water run-on is easily minimized by using standard civil engineering techniques such as diversion berms and drainage ditches (Smith, 1983). The design of a site utilizing surface caps or impermeable liners, or both, is based on a water balance for the site. Depicted in Figure IV.19 are the individual components of moisture at a site.

There are four combinations of capping and liners that could be used (in conjunction with surface water control measures) at a waste site, with these combinations depicted in Figure IV.20. The first type is called a natural attenuation site and utilizes neither capping or lining; it relies entirely on the pollutant attenuating capacity of the native soil. The second type of system utilizes an engineered liner (impermeable liner) to maximize the amount of leachate collected and minimize the amount escaping. The engineered cover (impermeable cap) sites are designed to minimize infiltration into the waste source by maximizing surface runoff and evapotranspiration. The combination engineered cover and liner (total containment) sites are designed to minimize infiltration and maximize the leachate collected, thus all but eliminating the escape of any leachate. The advantages and disadvantages of each type of system are outlined in Table IV.8.

Emrich, Beck and Tolman (no date) summarize a study of top-sealing a landfill to minimize leachate generation. Applications of liner

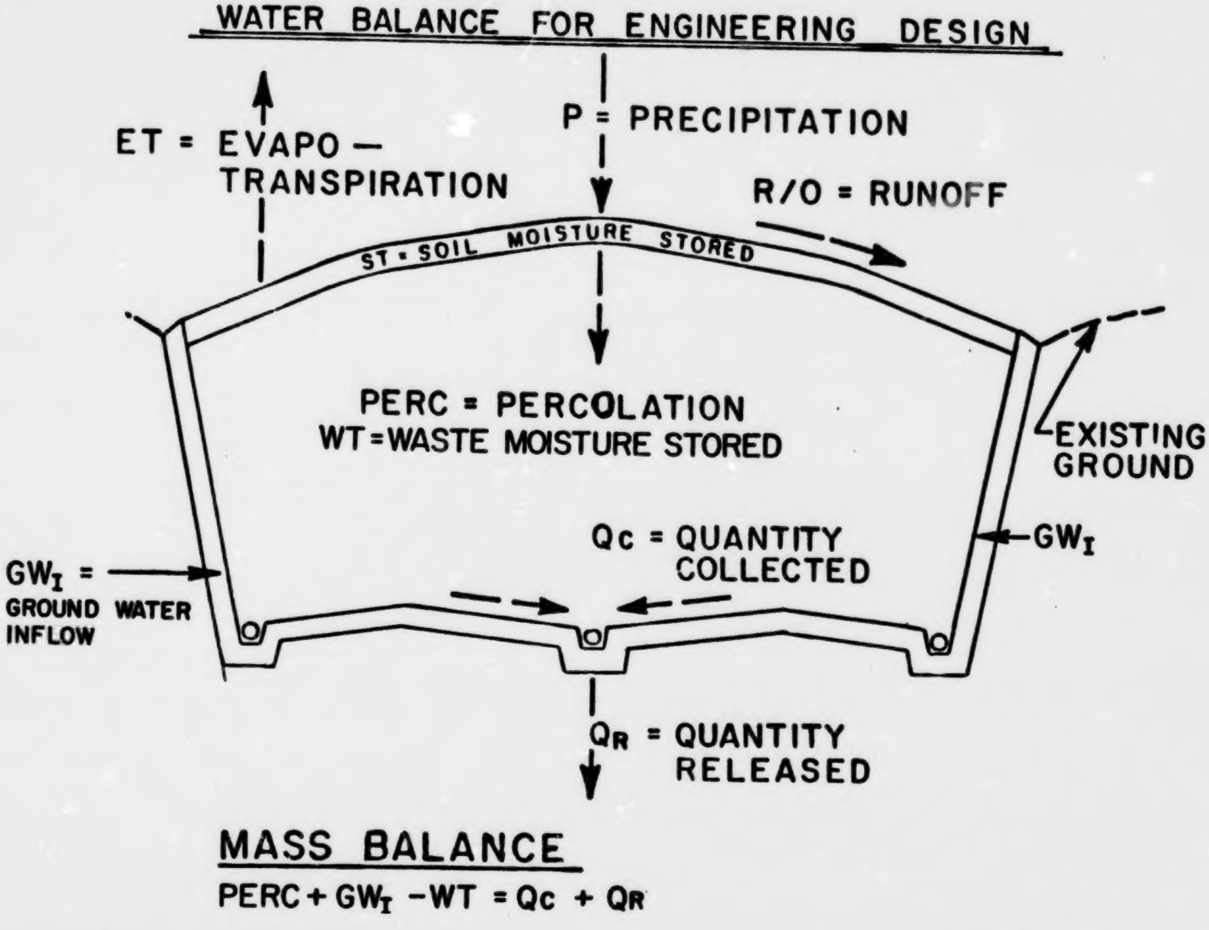
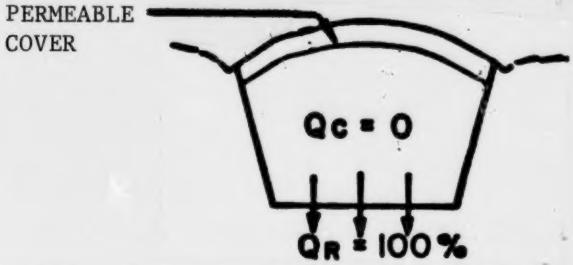
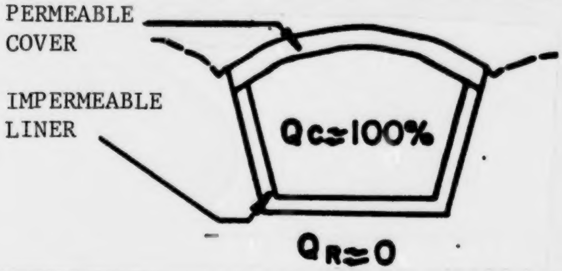

WATER BALANCE FOR ENGINEERING DESIGN
ET = EVAPO — TRANSPIRATION
P = PRECIPITATION
R/O = RUNOFF
ST = SOIL MOISTURE STORED
PERC = PERCOLATION
WT = WASTE MOISTURE STORED
EXISTING GROUND
Qc = QUANTITY COLLECTED
GWI
GWI = GROUND WATER INFLOW
QR = QUANTITY RELEASED
MASS BALANCE
PERC + GWI − WT = Qc + QR

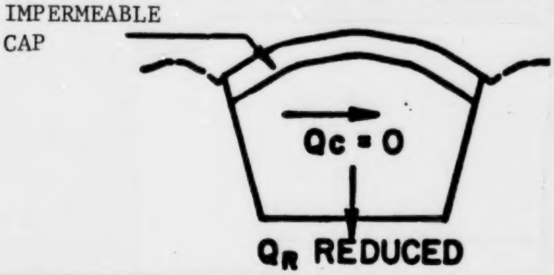
Figure IV.19: Moisture Components of Landfills (Smith, 1983).


PERMEABLE COVER
Qc = 0
QR = 100%

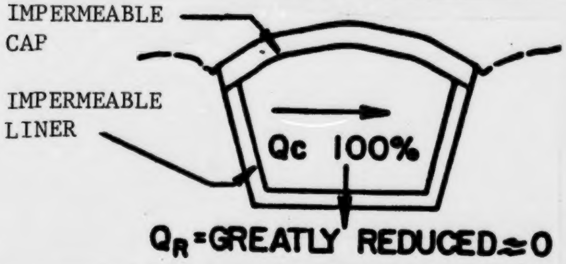
- Natural attenuation
- Leachate control minimal
- Address impacted environment - hydrogeological environment must be able to assimilate leachate without adverse impact
- Percolation very high, Q_R very high, Q_C very small


PERMEABLE COVER
IMPERMEABLE LINER
Qc≃100%
QR≃0

- Impede flow - collect and treat leachate
- Address impacted environment - impact of hydrogeological environment small. Place large emphasis on leachate treatment
- Percolation very high, Q_R very small, Q_C very large


IMPERMEABLE CAP
Qc = 0
QR REDUCED

- Natural attenuation
- Address impacted environment - lessens impact of natural attenuation design
- Percolation very low, Q_C very low, Q_R reduced


IMPERMEABLE CAP
IMPERMEABLE LINER
Qc 100%
QR=GREATLY REDUCED≃0

- Impede flow - collect and treat leachate
- Address impacted environment - impact on hydrogeologic environment low and also lessens leachate treatment impacts
- Percolation very low, Q_C low, Q_R greatly reduced

Figure IV.20: Four Combinations of Capping and Liners (Smith, 1983).

Table IV.8: Advantages/Disadvantages of Capping and Liners (Smith, 1983)

System (a)	Advantages	Disadvantages
Natural Attenuation	·No leachate collection, transport and treatment costs. ·Reduced construction costs.	·Requires unique hydrogeologic setting. ·Regulatory acceptance difficult to obtain. ·Long-term liabilities.
Engineered Liner	·Lessens hydrogeologic impact. ·Allows waste to stabilize quickly.	·"Clay-bowl" effect. ·Increased construction costs. ·Chance for surface discharge.
Engineered Cover	·Lessens hydrogeologic impact after closure. ·Reduces construction costs relative to liners.	·Increases closure costs. ·No leachate control during site operations. ·Long-term monitoring and land surface care.
Engineered Cover and Liner	·Lessens environmental impacts. ·Minimizes post closure leachate collection, transport and treatment costs. ·Politically/socially acceptable.	·High cost for engineering and construction. ·Need high quality clay or synthetic material. ·Lengthens time for waste stabilization.

(a) See Figure IV.21

technology are numerous and grow every year. Shultz and Miklas (1982) give an excellent discussion of the activities at fourteen lined facilities. Due to their potential for use in aquifer restoration projects, the emphasis herein will be on surface caps.

Construction -- Surface Capping

In general, the steps involved in the construction of an engineered cover site include:

(1) closure of facility for future receipt of waste materials;

(2) compaction of waste material and laying and working of suitable subbase;

(3) placement of impermeable membrane (surface cap);

(4) placement and working of suitable cover material over cap;

(5) revegetation; and

(6) regrading.

The key steps involved with surface capping are the placement of the impermeable membrane over the source of contamination, and the revegetation and regrading of the site. The regrading of the site should be done so as to maximize surface runoff and channel it away from the site. Revegetation allows for evapotranspiration of water that soaks into the cover soil, with surface capping being designed to prevent any remaining water from infiltrating into the waste and moving down to the ground water. Additional measures that should be included at most sites include installation of gas vents, and monitoring facilities for both surface water runoff and ground water.

Fung (1980) provides some general recommendations for layering the surface cap, assuming it is some type of soil or workable material, from the bottom up. These recommendations are:

(1) make buffer layer below barrier (cap) thick and dense enough to provide a smooth, stable base for compacting;

(2) compact all layers except topsoil and top lift of upper buffer;

(3) in barrier layer, strive for 90% of maximum density according to 5- or 15-blow compaction test;

(4) cover barrier layer soon enough to prevent extensive drying;

(5) provide sufficient design thickness to assure performance of layer function; specifying a 6 in. to 12 in. minimum should prevent excessively thin spots resulting from poor spreading techniques;

(6) construct in units small enough to allow rapid completion; and

(7) consider seeding topsoil at time of spreading.

Surface Capping -- Selection and Design Considerations

The materials used for covering or capping are many and varied. Fung (1980) groups these materials into natural soils, commercial cover materials, and waste materials. Soil has traditionally been used as a cover material at waste disposal sites. The cover has to fulfill several functions, and Table IV.9 summarizes the types of soil classified according to the Unified Soil Classification System (USCS) in terms of several functions (Fung, 1980). The rating of soils accomplished in Table IV.9 is based on the following points, with the functional ratings from I (best) to as many as XIII (poorest). Quantitative parameters are also provided wherever available, so that the absolute position of a particular soil rating can be seen (Fung, 1980).

(1) The first column in Table IV.9 concerns the Go-No Go aspect of trafficability. The ratings of I to XII from coarse granular

Table IV.9: Ranking of USCS Soil Types According to Performance of Cover Functions (Fung, 1980).

		(1)	(2)	(3)	(4)	(5)	(6)	(7)
		. . . . Trafficability		. . . .	. . Water Percolation . . .		. . . Gas Migration	
USCS Symbol	Typical Soils	Go-No Go (RCI Value)*	Stickiness (Clay, %)	Slipperiness (Sand-Gravel, %)	Impede (k, cm/s)*	Assist (k, cm/s)*	Impede (H_c, cm)*	Assist (H_c, cm)*
GW	Well-graded gravels, gravel-sand mixtures, little or no fines	I (>200)	I (0-5)	I (95-100)	X (10^{-2})	III (10^{-2})	X (6)	I (6)
GP	Poorly graded gravels, gravel-sand mixtures, little or no fines	I (>200)	I (0-5)	I (95-100)	XII (10^{-1})	I (10^{-1})	IX —	II —
GM	Silty gravels, gravel-sand-silt mixtures	III (177)	III (0-20)	III (60-95)	VII (5×10^{-4})	VI (5×10^{-4})	VII (68)	IV (68)
GC	Clayey gravels, gravel-sand-clay mixtures	V (150)	VI (10-50)	V (50-90)	V (10^{-4})	VIII (10^{-4})	IV —	VII —
SW	Well-graded sands, gravelly sands, little or no fines	I (>200)	II (0-10)	II (95-100)	IX (10^{-3})	IV (10^{-3})	VIII (60)	III (60)
SP	Poorly graded sands, gravelly sands, little or no fines	I (>200)	II (0-10)	II (95-100)	XI (5×10^{-2})	II (5×10^{-2})	VII —	IV —
SM	Silty sands, sand-silt mixtures	II (179)	IV (0-20)	IV (60-95)	VIII (10^{-3})	V (10^{-3})	VI (112)	V (112)
SC	Clayey sands, sand-clay mixtures	IV (157)	VII (10-50)	VI (50-90)	VI (2×10^{-4})	VII (2×10^{-4})	V —	VI —
ML	Inorganic silts and very fine sands, rock flour, silty or clayey fine sands, or clayey silts with slight plasticity	IX (104)	V (0-20)	VII (0-60)	IV (10^{-5})	IX (10^{-5})	III (180)	VIII (180)
CL	Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays	VII (111)	VIII (10-50)	VIII (0-55)	II (3×10^{-8})	XI (3×10^{-8})	II (180)	IX (180)
OL	Organic silts and organic silty clays of low plasticity	X (64)	V (0-20)	VII (0-60)	— —	— —	— —	— —
MH	Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts	VIII (107)	IX (50-100)	IX (0-50)	III (10^{-7})	X (10^{-7})	— —	— —
CH	Inorganic clays of high plasticity, fat clays	VI (145)	X (50-100)	X (0-50)	I (10^{-9})	XII (10^{-9})	I (200-400⁺)	X (200-400⁺)
OH	Organic clays of medium to high plasticity, organic silts	XI (62)	— —	— —	— —	— —	— —	— —
PT	Peat and other highly organic soils	XII (46)	— —	— —	— —	— —	— —	— —

Table IV.9: Continued

USCS Symbol	(8) Erosion Control Water (K-Factor)*	(9) Wind (Sand-Gravel, %)	(10) Reduce Freeze Action Fast Freeze (H_c, cm)*	(11) Saturation (Heave, mm/day)	(12) Crack Resistance (Expansion, %)	(13) Impede Vector Emergence	(14) Support Vegetation
GW	I (<0.05)	I (95-100)	X	I (0.1-3)	I (0)	X	X
GP	I —	I (95-100)	IX	I (0.1-3)	I (0)	X	X
GM	IV —	III (60-95)	VII	IV (0.4-4)	III —	VIII	VI
GC	III —	V (50-90)	IV	VII (1-8)	V —	V	V
SW	II (0.05)	II (95-100)	VIII	II (0.2-2)	I (0)	IX	IX
SP	II —	II (95-100)	VII	II (0.2-2)	I (0)	IX	IX
SM	VI (0.12-0.27)	IV (60-95)	VI	V (0.2-7)	II —	VII	II
SC	VII (0.14-0.27)	VI (50-90)	V	VI (1-7)	IV —	IV	I
ML	XIII (0.60)	VII (0-60)	III	X (2-27)	VI —	VI	III
CL	XII (0.28-0.48)	VIII (0-55)	II	VIII (1-6)	VIII (1-10)	III	VII
OL	XI (0.21-0.29)	VII (0-60)	—	VIII —	VII —	VI	IV
MH	X (0.25)	IX (0.50)	—	IX —	IX —	II	IV
CH	IX (0.13-0.29)	X (0-50)	I	III (0.8)	X (>10)	I	VIII
OH	VIII —	—	—	—	IX —	—	VIII
PT	V (0.13)	—	—	—	—	—	III

*RCI is rating cone index, k is coefficient of permeability, H_c is capillary head, and K-Factor is the soil erodibility factor. The ratings I to XIII are for best through poorest in performing the specified cover function.

Table IV.9: Continued

Note: Additional parameters are as follows:

Fire resistance	Same as Impede Gas Migration
Dust control	Same ranking and values as for Wind Erosion Control
Side slope stability	Determine on basis of laboratory testing
Side slope seepage	Same ranking and values as for Impede Water Percolation
Side slope drainage	Same ranking and values as for Assist Water Percolation
Discourage burrowing	Same ranking and values as for Slipperiness Trafficability
Discourage birds	All soils are suitable
Future use as natural settings	Same ranking as for Support Vegetation
Future use as foundation	Same ranking and values as for Go-No Go Trafficability

to fine peaty soils are based on the rating cone index values (RCI). The RCI expresses the probable strength of the specific site under repeated traffic. In column 2, stickiness trafficability is based on the weight percent of clay in the soil. Ranking for slipperiness trafficability in column 3 is similar to ranking in the previous column though based on a different parameter, sand and gravel percentage. Sand and gravel components decrease the slipperiness, i.e., improve the quality of soil from that functional point of view, by increasing frictional resistance. Attention is called to the fact that all three trafficability functions provide approximately the same soil ranking.

(2) Water percolation is addressed in columns 4 and 5. The best parameter for judging relative effectiveness for water percolation is the coefficient of permeability k, although it specifically reflects water movement in a saturated condition. The rankings in columns 4 and 5 are diametrically opposed, since one reflects impeded percolation and the other assisted percolation.

(3) Gas migration is addressed in columns 6 and 7 from contrasting viewpoints of impeded and assisted flow. The parameter on which the ranking is partly based is the capillary head (H_c) of the soil. This parameter reflects the tenacity with which the soil holds water.

(4) Two types of erosion control are considered in columns 8 and 9. Soils are rated for resistance to water erosion on the basis of values of the USDA soil erodibility K- factor. (K is the average soil loss in tons per acre per unit of rainfall and runoff erosivity factor (R), where R usually equals the pertinent rainfall index which is predictable from meteorological data.) For wind erosion resistance, soils are rated according to the sand and gravel content.

(5) Columns 10 and 11 concern cover functions of reducing freeze action. The fast freezing/fast thawing aspects, which also involve the tendency to freeze to greater depths, give soil ratings of I to X based on the capillary head. Ranking for crack resistance involves considerable judgment. It is, however, well-known that the extreme cracking is almost restricted to soils with high clay content, and only those soils rated VIII or worse should cause much concern.

(6) In order to impede vector emergence, a soil with a high clay content or well-graded combination of clay and silt, with or without sand, is preferred. Loamy soils are somewhat more suitable for supporting vegetation than soils at the sand, silt, and clay extremes of grain-size distribution. Thus, a ranking of cover soil for supporting vegetation in column 14

gives the high positions, somewhat subjectively, to loam and other well-graded mixtures. The fire resistance ranking is the same as that for impede gas migration in column 6, since fire resistance is increased if gas movement is impeded.

(7) With dust control, fine-grained particles are essential for dust, so that the appropriate quantitative rating parameter is considered to be the sand and gravel content. The ranking, therefore, is the same as for wind erosion control.

(8) Important aspects of the side slope cover are stability, seepage, and drainage. The seepage and drainage aspects have rankings and rating values identical to those for impede water percolation and assist water percolation, respectively. The stability of side slopes may in some cases be a very important function of the cover. In such cases, the choice of soil should be carefully considered and based on laboratory strength tests.

(9) The effectiveness of soils for discouraging burrowing animals is believed to increase with the percentage of sand content. Accordingly, the same ranking is used as was used for slipperiness trafficability, since in both cases the important parameter is sand and gravel content. Soil type is apparently not a pertinent consideration in discouraging birds, so no preference is given in the table.

(10) For the long-range future use of a landfill site for natural or parklike settings, the ranking should be the same as for supporting vegetation. Where the future use of the landfill will be to support pavement or light structures, a major concern is for high modulus. This aspect of cover soil is adequately reflected in RCI values as for go-no go trafficability. It should be remembered, however, that the supportive capability of the underlying solid waste is commonly the critical factor.

After selection of the soil for covering the waste, efforts should be directed to the most effective placement and treatment. Soil cover can be improved in several ways as it is constructed. Materials may be added for better gradation, hauling and spreading equipment can be operated beneficially, and the base or internal structure of the cover system may be improved. Soil blending increases the expense of surface capping operations and, therefore, has usually not been duly considered.

The benefits derived from blending, however, are sometimes dramatic through the alteration of grain-size distribution or average grain size. Blending may be done in place using a blade or harrow. Examples of materials used for blending include gravel, sand, silt, clay (Fung, 1980).

Soils to be used for surface capping may also be improved through blending with additives and/or cements. Additives and cements are defined as synthetic materials added in relatively small amounts to soil to achieve beneficial effects. Classifications include strengthening cements or stabilizers, dispersants, freeze-point suppressants, water repellants, and dust palliatives. Factors that enter into determining the cost effectiveness of additives and cements are their relatively high unit cost, manner of addition or incorporation, and duration of effect. A major concern in using any cover system with increased strength is the remaining susceptibility to cracking as a result of differential settlement or environmental deterioration, such as freeze-thaw; plans for patching repairs are essential. Examples of additives and cements which could be used are as follows (Fung, 1980):

(1) Soil-Cement -- Soil cement is composed of sandy soil, portland cement, and water that have reacted and hardened. About 8% of dry cement is incorporated in place and compacted after water is added to about optimum content. Pre-mixing and placement wet is another method that seems less amenable to covering waste because of extra costs, except possibly on steep slopes. Somewhat higher cement content is needed in poorly graded soils or where fines are lacking, but correspondingly less for well-graded mixtures.

(2) Soil-Bitumen -- Bitumen stabilizes sandy soils by cementing and water-proofing. An optimum content increases the cohesion of the soil, yet does not separate grains enough to reduce frictional strength. From 4 to 8% bitumen (soil dry weight basis) is recommended as a first cut for sandy loam to be

refined subsequently by testing mixtures of various contents. Sand should require somewhat less bitumen.

(3) Cement-Treated Soil -- Incorporation of as little as 1% of Portland cement has been shown to have stabilizing effects on granular soil.

(4) Lime-Treated Soil -- Lime (calcium oxide or hydroxide) is principally mixed into clayey soils for its effects as a flocculant or base exchanger. However, lime also promotes some beneficial pozzolanic reaction in fine, cohesive soils, and strengthening may continue for many weeks of curing.

(5) Fly Ash-Lime (or Cement-)-Treated Soil -- Fly ash is attractive as an additive to soil because of its pozzolanic properties (i.e., although not a cement itself, fly ash develops cementitious properties with lime or cement and water). Accordingly, a small amount of lime or Portland cement should be included unless self-hardening has been confirmed by test or previous experience with the particular fly ash.

(6) Fly Ash-Treated Soil -- Some fly ashes possess moderate self-hardening characteristics when moistened and compacted and, therefore, offer promise alone as major additions to cover waste. This phenomenon is partly due to the free lime content of the ash itself. Laboratory tests or field trials will be necessary to establish such useful peculiarities of specific fly ash sources where previous experience is lacking.

(7) Fly Ash-Lime (or Cement)-Sulfate-Treated Soil -- This mixture is proposed as a locally viable option for covering waste following research on the uses of fly ash-lime-sulfate (or sulfite).

(8) Dispersants -- Several soluble salts act as dispersing agents and are recommended for improving soil compaction and reducing k. The treatment is primarily for fine-grained soils containing clay minerals. Better compaction can be achieved on coarse-grained soils by other means, such as blending in fine material. Dispersion (deflocculation) involves the breakdown of clayey aggregates into the individual mineral particles. The effect is to increase dry unit weight, to lower permeability, and incidently, to facilitate compaction. Three dispersing agents have been found notably effective. Common sodium chloride produces satisfactory results in many cases and is inexpensive. Tetra-sodium pyrophosphate and sodium polyphosphate appear to have slight advantages in many cases over sodium chloride.

(9) Swell Reducers -- Lime is the principal additive for reducing shrink/swell behavior in clay-rich soils. About 5% is optimum for effecting ion exchange (calcium for sodium), flocculation, and cementation. Quicklime contains more calcium and, therefore, is preferred to hydrated lime by some users provided a mellowing period is allowed for homogenization.

(10) Freeze-Point Suppressant -- Poor compaction can result when soil pore water is frozen during cold weather operations. Ordinarily soils construction for roads, etc., is curtailed in the winter to avoid the poor results. Some improvements can be achieved by adding a freeze-point suppressant and may be advisable where covering operations are expected to continue during cold spells. Calcium chloride can be effective, either in solution or in dry, flaked form.

Layering is perhaps the most promising, yet presently underutilized, technique for designing final solid waste cover. By combining two or three distinct materials in layers, the designer may mobilize favorable characteristics of each together at little extra expense. The systematics are briefly set forth there. Figure IV.21 schematically illustrates a layered system (Fung, 1980). A layered system may include topsoil, barrier layer, buffer layer, water drainage layer, filter and gas drainage layer. Comments on each of these layers are as follows (Fung, 1980).

(1) Topsoil -- A topsoil or a subsoil made amenable to supporting vegetation frequently forms the top of a layered cover system. Untreated subsoils are seldom suitable directly, so it has been often necessary to supplement subsoil with fertilizers, conditioners, etc., to obtain the desired result.

(2) Barrier Layer or Membrane -- The primary feature in many layered systems is the barrier. This layer functions to restrict passage of water or gas. Barrier layers are almost always composed of clayey soil that has inherently low permeability; USCS types CH, CL and SC are examples of soil types. Soil barriers are susceptible to deterioration by cracking when exposed at the surface, so that a buffer layer is recommended to protect the clay from excessive drying. Synthetic membranes may be used in place of soil barriers. Costs are generally high in comparison to available soils, and

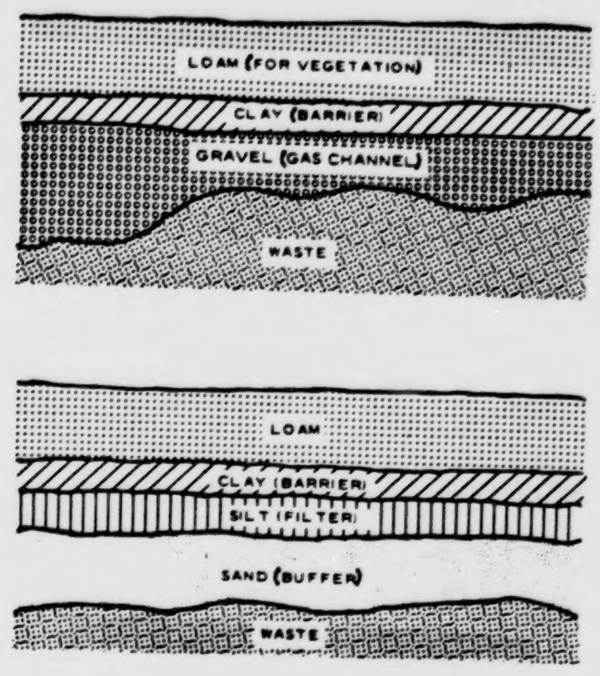

LOAM (FOR VEGETATION)
CLAY (BARRIER)
GRAVEL (GAS CHANNEL)
WASTE
LOAM
CLAY (BARRIER)
SILT (FILTER)
SAND (BUFFER)
WASTE

Figure IV.21: Typical Layered Cover Systems (Fung, 1980).

problems in placement or with deterioration may arise. Nevertheless, membranes are a viable option.

(3) Buffer Layer -- A buffer layer may be described as a random layer having a subordinate covering function and characteristics in comparison with the adjacent layer. The principal service of a buffer is to protect a barrier layer or membrane located above or below. The buffer shields a vulnerable, thinner barrier or sheet from tears, cracks, offsets, and punctures. Below a barrier, the buffer layer also provides a smooth, regular base. Any soil type will serve as a buffer ordinarily, but it should be free of clods.

(4) Water Drainage Layer or Channel -- A water drainage layer, blanket, or channel may be designed into the cover in numerous ways to provide a path for water to exit rapidly. Poorly graded sand and gravel are possibilities as effective drainage materials, i.e., soils classified GP and SP.

(5) Filter -- Where layers with grossly discordant grain sizes are joined, there may be a tendency for fine particles to penetrate the coarser layer. As a result, the effectiveness of the coarse layer for water drainage may be reduced by clogging of pores. Removals from the fine layer may promote additional bad effects, such as internal erosion and settlement. A filter layer with a material such as silt may be desirable.

(6) Gas Drainage Layer and Vents -- A gas drainage layer has consistency and configuration similar to those of the water drainage layer or channel. Both layer types function to transmit preferentially. The position in the cover system is the main distinction. The gas drainage layer is placed on the lower side to intercept gases rising from waste cells, whereas the drain for water is positioned on the upper side to intercept water percolating from the surface. Gas vents are frequently used in the present state-of-the-art in municipal waste landfilling. It has been found that dangerous concentrations of flammable gases can accumulate if not vented properly to the atmosphere. Figure IV.22 illustrates two recommended gas vents.

Commercially-available capping materials or membranes may be preferable to soil-based systems over wastes that pose a high risk of serious pollution (where not properly shielded). Examples of commercial materials include bituminous and Portland cement concrete barriers, and membranes of various types functioning alone or in conjunction with soil

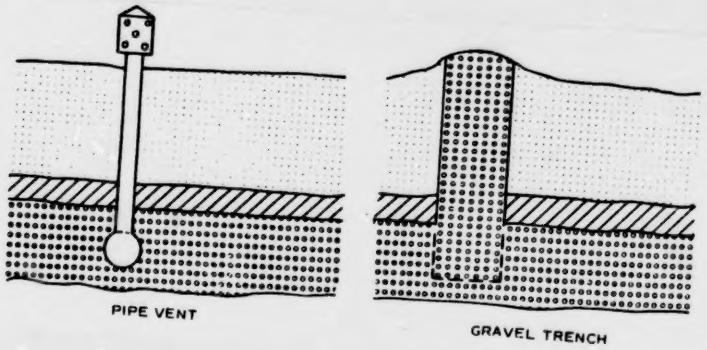

PIPE VENT
GRAVEL TRENCH

Figure IV.22: Two Types of Gas Vents for Layered Cover Systems (Fung, 1980).

or granular waste layers to exclude water. A summary of commercial materials and their characteristics is presented elsewhere (Fung, 1980).

A number of factors should be considered in the selection of a commercial cover material. Important characteristics of flexible membranes and rigid barriers include vulnerability to tearing or cracking, respectively. A smooth buffer of sand should reduce membrane puncture during construction, but extra long-term planning will be necessary against stressing effects of differential settlement. The rigid barriers sometimes have an advantage because cracks can be exposed, cleaned, and repaired (sealed with tar) with relative ease. Deterioration is another major problem for serious consideration. Concrete barriers are susceptible to chemical deterioration in harsh environments such as those rich in sulfates. Sunlight, burrowing animals, and plant roots increase the deterioration of membranes. Twenty years is about the extent of experience with membranes. Longer design service life may be somewhat risky in adverse environments and conditions. The cost of commercial coverings will often be the overriding consideration (Fung, 1980).

The other category of nonsoil materials that is available for covering waste ranges through a long and diverse list of granular wastes (some are in fact soils). An economic advantage may accrue from using these inexpensive, locally generated wastes in place of scarce, indigeneous soils. Examples of waste materials used for covers include fly ash, fly ash modified with lime to enhance cementation, bottom ash and slag, furnace slag (from iron steel), incinerator residue, foundry sand, mine and pit wastes, mine mill tailings, plant sludges, reservoir and channel silt, dredged material, and composted sewage sludge (Fung, 1980).

Costs

The general range for costs of surface caps is $20,000 to $30,000 per acre covered, while the cost for installing a liner is more expensive, being in the range of $40,000 to $50,000 per acre. Cost estimates for various liners are outlined in Table IV.10.

SHEET PILING

Sheet piling involves driving lengths of steel that connect together into the ground to form a thin impermeable permanent barrier to flow. Sheet piling materials also include timber and concrete, however, their application to polluted ground water situations would be doubtful due to corrosive actions and costs, respectively.

Construction

Sheet piling requires that the steel sections be assembled prior to being driven into the ground. The lengths of steel have connections along both edges. The connections may be either slotted or ball- and socket-types. The sections are then driven individually into the ground by use of a pile hammer. The types of pile hammers include: drop; single-acting steam; double-acting steam; diesel; vibratory; and hydraulic. For each type of hammer listed the driving energy is supplied by a falling mass, which strikes the top of the pile (Bowles, 1977). After the piles have been driven to their desired depth, the remaining above-ground portions are cut off. Initially, sheet piles are

Table IV.10: Costs for Various Sanitary Landfill Liner Materials (Haxo, 1973)

Material	Installed Cost[a] ($/sq yd)
Polyethylene (10-20[b] mils[c])	0.90 - 1.44
Polyvinyl chloride (10-30[b] mils)	1.17 - 2.16
Butyl rubber (31.3-62.5[b] mils)	3.25 - 4.00
Hypalon (20-45[b] mils)	2.88 - 3.06
Ethylene propylene diene monomer (31.3-62.5[b] mils)	2.43 - 3.42
Chlorinated polyethylene (20-30[b] mils)	2.43 - 3.24
Paving asphalt with sealer coat (2 inches)	1.20 - 1.70
Paving asphalt with sealer coat (4 inches)	2.35 - 3.25
Hot sprayed asphalt (1 gallon/yd^2)	1.50 - 2.00 (includes earth cover)
Asphalt Sprayed on Polypropylene fabric (100 mils)	1.26 - 1.87
Soil-bentonite (9.1 lbs/yd^2)	0.72
Soil-bentonite (18.1 lbs/yd^2)	1.17
Soil-cement with sealer coat (6 inches)	1.25

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[a] Cost does not include construction of subgrade nor the cost of earth cover. These can range from \$0.10 to \$0.50/yd^2/ft of depth.

[b] Material costs are the same for this range of thickness.

[c] One mil = 0.001 inch.

not totally impermeable because of small gaps in the connections. As time passes, these gaps are closed as ground water flow carries fine particles into the gaps and closes them by clogging.

Steel sheet piling can be considered permanent because experience has shown that corrosion is not a factor in causing failures (Bowles, 1977). One strong advantage of sheet piling is that the sections are reusable and do not have to be left in place permanently. If conditions permit, steel piles may be removed and reused.

Costs

In situations where the function of the sheet pile is just to restrict ground water flow, i.e., no significant load resistance is required, a light weight steel will be adequate. Construction costs of a 1700 foot long and 60 foot deep light-weight steel cut-off wall was reported to range from $650,500 to $956,000 (Tolman, et al., 1978). To date, sheet piling has been proposed as a means of ground water pollution control, but specific applications have been minimal, if any.

Advantages and Disadvantages

Construction of steel sheet piles as a means of ground water control can potentially be effective and economical in specific cases. In general, however, this is probably an over-elaborate technique to achieve a relatively simple result. As the size of a project increases, sheet piling will become uneconomical because of high material and shipping costs. In addition, pile driving requires a relatively uniform, loose, boulder-free soil for ease of construction. Other advantages/disadvantages are listed in Table IV.11 (Tolman, et al., 1978).

GROUTING

Grouting is the process of injecting a liquid, slurry, or emulsion under pressure into the soil. The fluid injected will move away from the point of injection to occupy the available pore spaces. As time passes, the injected fluid will solidify, thus resulting in a decrease in the original soil permeability and an increase in the soil-bearing capacity. Grouts are usually classified as particulate or chemical. Particulate grouts consist of water plus particulate material which will solidify within the soil matrix. Chemical grouts usually consist of two or more liquids which will gel when they come in contact with each other. Listed in Table IV.12 are materials commonly used for grouts. Table IV.13 identifies the properties of cement grout additives.

Construction

Two of the more popular methods of grout installation are the stage and packer methods. In stage grouting, holes are drilled to the geologic seam closest to the land surface and the grouting fluid is injected. The holes are then cleaned, drilling continues down to the next seam and grouting continues. The process is repeated until a sufficient depth has been obtained. In general, the stage method proceeds downward, utilizing increasing injection pressures. In the packer method, holes are drilled to the maximum planned depth. A zone of specified thickness is then partitioned off by placing packers at the top and bottom of the zone. Grout is then injected into the zone

Table IV.11: Advantages/Disadvantages of Steel Sheetpiles (Tolman, et al., 1978)

Advantages	Disadvantages
1. Construction is not difficult; no excavation is necessary.	1. The steel sheet piling initially is not watertight.
2. Contractors, equipment, and materials are available throughout the United States.	2. Driving piles through ground containing boulders is difficult.
3. Construction can be economical.	3. Certain chemicals may attack the steel.
4. No maintenance required after construction.	
5. Steel can be coated for protection from corrosion to extend its service life.	

Table IV.12: Materials Commonly Used for Grout

cement, water
cement, rock flour, water
cement, clay, water
cement, clay, sand, water
asphalt
clay, water
chemical

Table IV.13: Properties of Admixtures Used with Cement Grouts

Admixture	Property
Calcium chloride Sodium hydroxide Sodium silicate	Accelerates setting time
Gypsum Lime sugar Sodium tannate	Retards setting time
Finely ground bentonite	Increases plasticity Reduces grout shrinkage
Clay Ground shale Rock flour	Reduces cost of grout Reduces strength of grout

between the two packers. The mechanism is then moved up to the next zone to be grouted and the process is repeated. The packer method moves upward from the bottom utilizing decreasing injection pressures. Advantages of the packer method include: grouting pressures can be adjusted specifically to a particular foundation depth; walls of the borehole remain smooth and an excellent seal with packers can be achieved; and high pressures used in the stage method which may cause fracturation are avoided. However, these advantages can be offset by increased equipment needs and time for installation (Bowen, 1981).

Another method of grout injection is the driven-rod method. In this method, a perforated rod is driven to a desired depth and grout is injected as the rod is slowly withdrawn. This method is limited to shallow depths and relatively boulder-free soils.

Problems that might arise during construction of grout systems include: leakage of grout around the injection pipe of the hole being grouted; loss of presssure below the water table resulting in sand and water being forced into the pipe; and grout surfacing in outlying areas due to lateral migration (Bowen, 1981). It is also desirable to deposit cement grouts in clean seams from which any clay or unconsolidated materials have been removed, thus adding the burden of washing boreholes (Peurifoy, 1979).

Construction of grout cutoff walls requires certain equipment in addition to normal borehole or drilling equipment. The list includes one or more air compressors; one or two grout mixers; one agitator-type reservoir tank; one or more grout pumps; and grout discharge pipes or hoses, valves, and pressure gauges (Peurifoy, 1979).

Design

The first consideration in the design of a grout cutoff system is the actual composition of the grout. The composition will be a function of several variables including: the soil type to be injected into; the pollutant to be inhibited; the time since pollution started; and the time for installation. In general, chemical grouts must be used in fine-grained soils. However, chemical grouts (usually silicate) are not suitable for highly acidic or alkaline environments because their gel formation is an acid-base reaction. For coarse or gravel soils, particulate grouts are suitable. The amount of cement or bentonite in a particulate grout varies widely. The quantity of bentonite which can be incorporated in a grout is dependent upon the following considerations: the workability of the mixture, increased bentonite concentrations increase the stiffness of the slurry until it may become unpumpable; adding bentonite to cement slurries decreases their compressive strength; increased bentonite concentrations yield lower specific gravity slurries showing a reduced tendancy to migrate through the soil after placement; and increased bentonite concentrations reduce settlement or sedimentation of the slurries before injection (Jones, 1963).

A general guide for the selection of grouts is shown in Figure IV.23. Knowing the soil type in the area to be protected, Figure IV.23 can be entered from the top to determine both the applicable types of grouts and the available grouting procedures. The range of soil types to which a particular type of grout is applicable is covered by the solid white horizontal bars. The range of soil types to which a

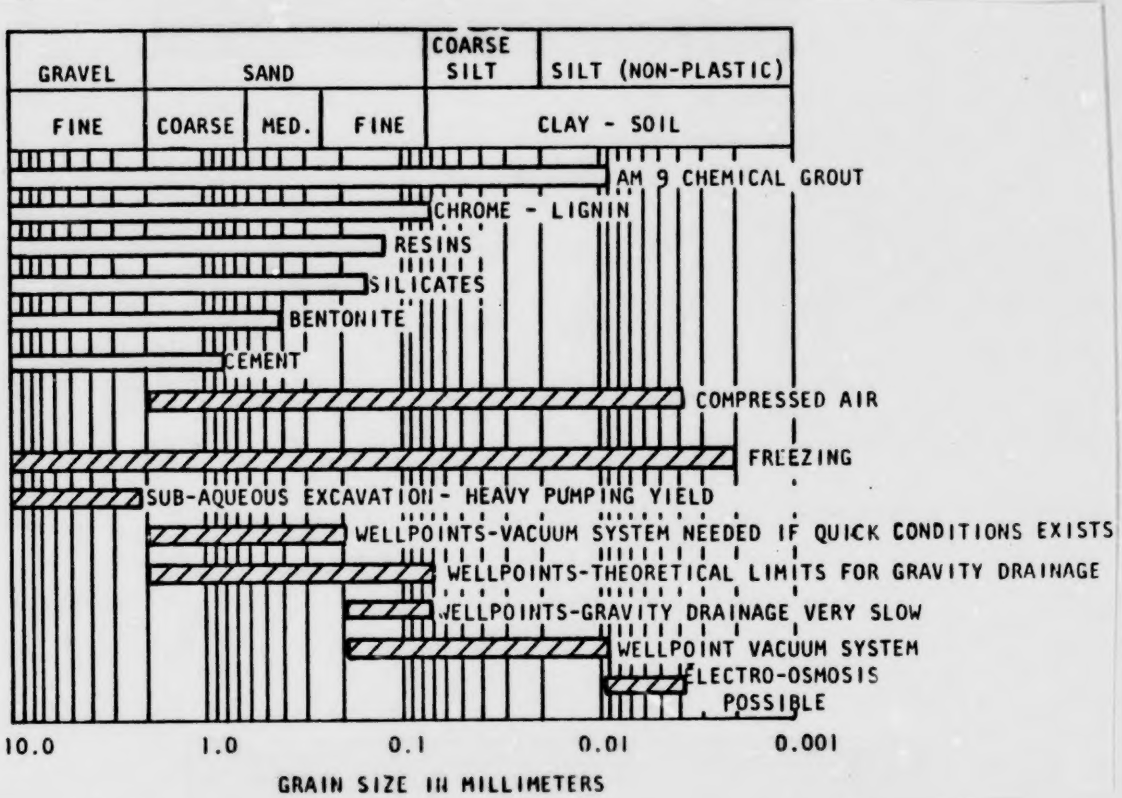


Figure IV.23: Soil Gradation Limits for Grout Injection (from American Cyanamid Company).

particular grouting procedure is applicable is indicated by the cross-hatched bars. Tables IV.14 to IV.16 summarize the compatibility of grouts with several contaminant types.

The second design consideration is the pressure at which the grout is to be injected. The use of excess pressures may weaken the strata by fissuring the rock or by opening fissures in otherwise closely-jointed rock. Pressure-induced fissures will result in the wastage of grout. In contrast, the pressure should be kept sufficiently high to ensure penetration of the grout and decrease the time required for grouting. The allowable grouting pressure is best determined by conducting hydraulic fracture tests in the strata to be grouted (Morgenstern and Vaughan, 1963).

A number of chemical grouting agents have been banned or their use discontinued because of their toxicity. Huibregtse and Kastman (1981) note that one of the most successful grouts, AM-9, is highly toxic and has been removed from most markets because of its potential undesirable effects on ground water. Other grouts considered to be toxic and presenting a potential for ground water pollution are the lignin- and formaldehyde-based grouts.

Costs

The costs for grout cutoff systems are high, hence they will be applicable only to small localized cases of ground water pollution. Costs have been reported to range from $142 to $357 per installed cubic foot (Lu, Morrison and Stearns, 1981). Table IV.17 lists the relative costs of different types of grout.

Table IV.14: Interactions Between Grouts and Generic Chemical Classes (Hunt, et al., no date)

Grout Type / Chemical Group	Bitumen	Portland Cement		Clay (Bentonite)	Clay-Cement	Silicate	Polymers					
		Type I	Type II and V				Acrylamide	Phenolic	Urethane	Urea-formaldehyde	Epoxy	Polyester
Acid	?a	1d	1d	?c	?c	3a	2c	?a[@]	2c	1a	?a[@]	?d
Base	?a	1d	1a[+]	?c[#]	?d	2c	3d	?d	?d	2c	?a	?d
Heavy Metals	?	1a	?	?d	?	3?	3?	?	?	?	?	?
Non-Polar Solvent	?d	2c	2?	?d	?	?	?a	?d	?a	2?	?d	?d
Polar Solvent	?d	2c	2?	?d	?	?	?	?d	?a	2?	?d	?d
Inorganic Salts	?d	2c	2a	2d	?d[·]	3?	3d[*]	3a	?d	?a	?a	?

KEY: Compatibility Index

Effect on Set Time: 1=No significant effect: 2=Increase in set time (lengthen or prevent from setting); 3=Decrease in set time.

Effect on Durability: a=No significant effect; b=Increase durability; c=Decrease durability (destructive action begins within a short time period); d=Decrease durability (destructive action occurs over a long time period).

[·] Except sulfates, which are ?c

[*] Except heavy metal salts which are 2

[@] Non-oxidizing

[+] Except KoH and NaOH, which are 1d

[#] Modified bentonite is d

?Data unavailable

Table IV.15: Interactions Between Grouts and Specific Chemical Groups (Hunt, et al., no date)

Grout Type / Chemical Group	Bitumen	Portland Cement		Clay (Bentonite)	Clay-Cement	Silicate	Polymers					
		Type I	Type II and V				Acrylamide	Phenolic	Urethane	Urea-formaldehyde	Epoxy	Polyester
Organic Compounds												
Alcohols and Glycols	?a	?d	?d	?d	?d	?	?d	?	3a	?	?a	?a
Aldehydes and Ketones	?d■	?	?	?d	?	?	?a	3a	?d	?	?	?
Aliphatic and Aromatic Hydrocarbons	?d	2a	2?	?d	?	?	?a	?d‡	?a	2a	?d	?d
Amides and Amines	?	?	?	?	?	?	?	?	3?	?	?	?
Chlorinated Hydrocarbons	?d	2d	2d	?	?	?	?a	?d	?a	2a	?d	?d
Ethers and Epoxides	?	?	?	?	?	?	?a	?	?a	?d	?	?
Heterocyclics	?	?	?	?d	?	?	?a	?	?	?	?	?
Nitriles	?	?	?	?	?	?	?	?	?	?	?	?
Organic Acids and Acid Chlorides	?a	1d	1d	?d	?d	?a	2a	?a	2a	1a	?d	?d
Organometallics	?	?	?	?	?	?	?	?	?	?	?	?
Phenols	?d	1d	?	?d	?d	?	?	2a	?c	?	?	?
Organic Esters	?	?	?	?	?	1a	?	?	?	?	?	?
Inorganic Compounds												
Heavy Metal Salts and Complexes	?d	2c	2a	?d	2c	3?	2?	?	?	?a	?	?
Inorganic Acids	?a§□	1d	1a	?c►	?c	3a	2c	?a§	2c	1d	?a§	?a★
Inorganic Bases	?a	1a	1a†	?c►	?d	2c	3d	?d	?d	2c	?a	?d
Inorganic Salts	?d	2c	2a	2d	?d*	3?	3d	3a#	?d	?a	?a	?a

KEY: Compatibility Index

Effect on Set Time

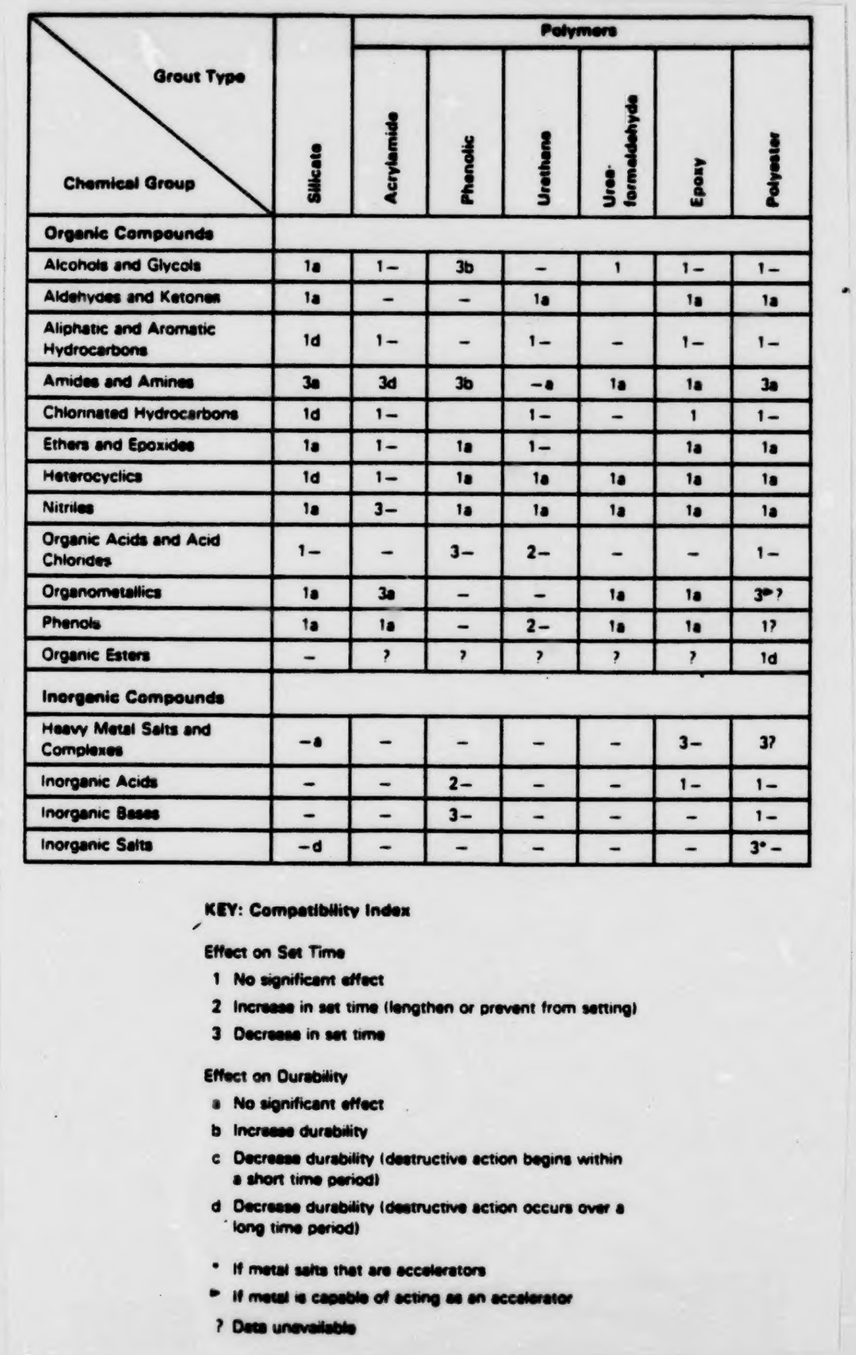
1 No significant effect
2 Increase in set time (lengthen or prevent from setting)
3 Decrease in set time

Effect on Durability

a No significant effect
b Increase durability
c Decrease durability (destructive action begins within a short time period)
d Decrease durability (destructive action occurs over a long time period)

* Except sulfates, which are ?c
† Except KoH and NaOH, which are 1d
‡ Low molecular weight polymers only
§ Non-oxidizing
★ Non-oxidizing, except HF
□ Except concentrated acids
■ Except aldehydes which are 1a
# Except bleaches which are 3d
► For modified bentonites, ?d
? Data unavailable

Table IV.16: Predicted Grout Compatibilities (Hunt, et al., no date)



Grout Type / Chemical Group	Silicate	Polymers					
		Acrylamide	Phenolic	Urethane	Urea-formaldehyde	Epoxy	Polyester
Organic Compounds							
Alcohols and Glycols	1a	1 –	3b	–	1	1 –	1 –
Aldehydes and Ketones	1a	–	–	1a		1a	1a
Aliphatic and Aromatic Hydrocarbons	1d	1 –	–	1 –	–	1 –	1 –
Amides and Amines	3a	3d	3b	– a	1a	1a	3a
Chlorinated Hydrocarbons	1d	1 –		1 –	–	1	1 –
Ethers and Epoxides	1a	1 –	1a	1 –		1a	1a
Heterocyclics	1d	1 –	1a	1a	1a	1a	1a
Nitriles	1a	3 –	1a	1a	1a	1a	1a
Organic Acids and Acid Chlorides	1 –	–	3 –	2 –	–	–	1 –
Organometallics	1a	3a	–	–	1a	1a	3► ?
Phenols	1a	1a	–	2 –	1a	1a	1?
Organic Esters	–	?	?	?	?	?	1d
Inorganic Compounds							
Heavy Metal Salts and Complexes	– a	–	–	–	–	3 –	3?
Inorganic Acids	–	–	2 –	–	–	1 –	1 –
Inorganic Bases	–	–	3 –	–	–	–	1 –
Inorganic Salts	– d	–	–	–	–	–	3• –

KEY: Compatibility Index

Effect on Set Time

1 No significant effect
2 Increase in set time (lengthen or prevent from setting)
3 Decrease in set time

Effect on Durability

a No significant effect
b Increase durability
c Decrease durability (destructive action begins within a short time period)
d Decrease durability (destructive action occurs over a long time period)

• If metal salts that are accelerators
► If metal is capable of acting as an accelerator
? Data unavailable

Table IV.17: Relative Costs of Grout*

Type of Grout	Basic Cost Figure
Portland cement	1.0
Silicate base - 15 percent	1.3
Lignin base	1.65
Silicate base - 30 percent	2.2
Silicate base - 40 percent	2.9
Urea formaldehyde resin	6.0
Acrylamide (AM-9)	7.0

* Base unit = 1.0. Under a given set of conditions, where portland cement grout costs 1.0 times $/unit, other types of grout will cost the given figure times $/unit. (Tolman,etal., 1978).

Advantages and Disadvantages

The technology of grouting has been used in the construction industry for years. To date, most applications of grouting technology have been for increasing a soils' bearing capacity (to aid in tunnel construction for example) or to decrease the permeability of a soil to inhibit water movement (such as a cutoff wall for a dam). The applications of this technology to ground water pollution control are very recent. For example, Huibregtse and Kastman (1981) have analyzed the feasibility of mobile grouting units for protecting ground water threatened by hazardous spills on land. A number of physical/chemical advantages and disadvantages for grouting are listed in Table IV.18.

SLURRY WALLS

Slurry walls represent a technology for encapsulating an area to either prevent ground water pollution or restrict the movement of previously-contaminated ground water. The technology involves digging a trench around an area and backfilling with an impermeable material. Slurry walls can either be placed upgradient from a waste site (Figure IV.24) to prevent flow of ground water into the site, or placed around a site (Figure IV.25) to prevent movement of polluted ground water away from a site. Usually, slurry walls will require a complementary technology such as surface capping or purge wells.

Construction

The most common type of slurry wall construction is the trench method. In this method a trench is excavated, in the presence of a bentonite-water slurry, to a desired depth. After excavation, the

Table IV.18: Advantages/Disadvantages of Grout Systems

Advantages[a]	Disadvantages
1. When designed on basis of thorough preliminary investigations, grouts can be very successful.	1. Grouting limited to granular types of soils that have a pore size large enough to accept grout fluids under pressure yet small enough to prevent significant pollutant migration before implementation of grout program.[b]
2. Grouts have been used for over 100 years in construction and soil stabilization projects.	2. Grouting in a highly layered soil profile may result in incomplete formation of a grout envelope.[b]
3. Many kinds of grout to suit a wide range of soil types are available.	3. Presence of high water table and rapidly flowing ground water limits groutability through; a. extensive transport of contaminants. b. rapid dilution of grouts[b]
	4. Some grouting techniques are propietary.[a]
	5. Procedure requires careful planning and pretesting. Methods of ensuring that all voids in the wall have been effectively grouted are not readily available.[a]

(a) Tolman,et al.,1978.
(b) Huibregtse and Kastman, 1981.

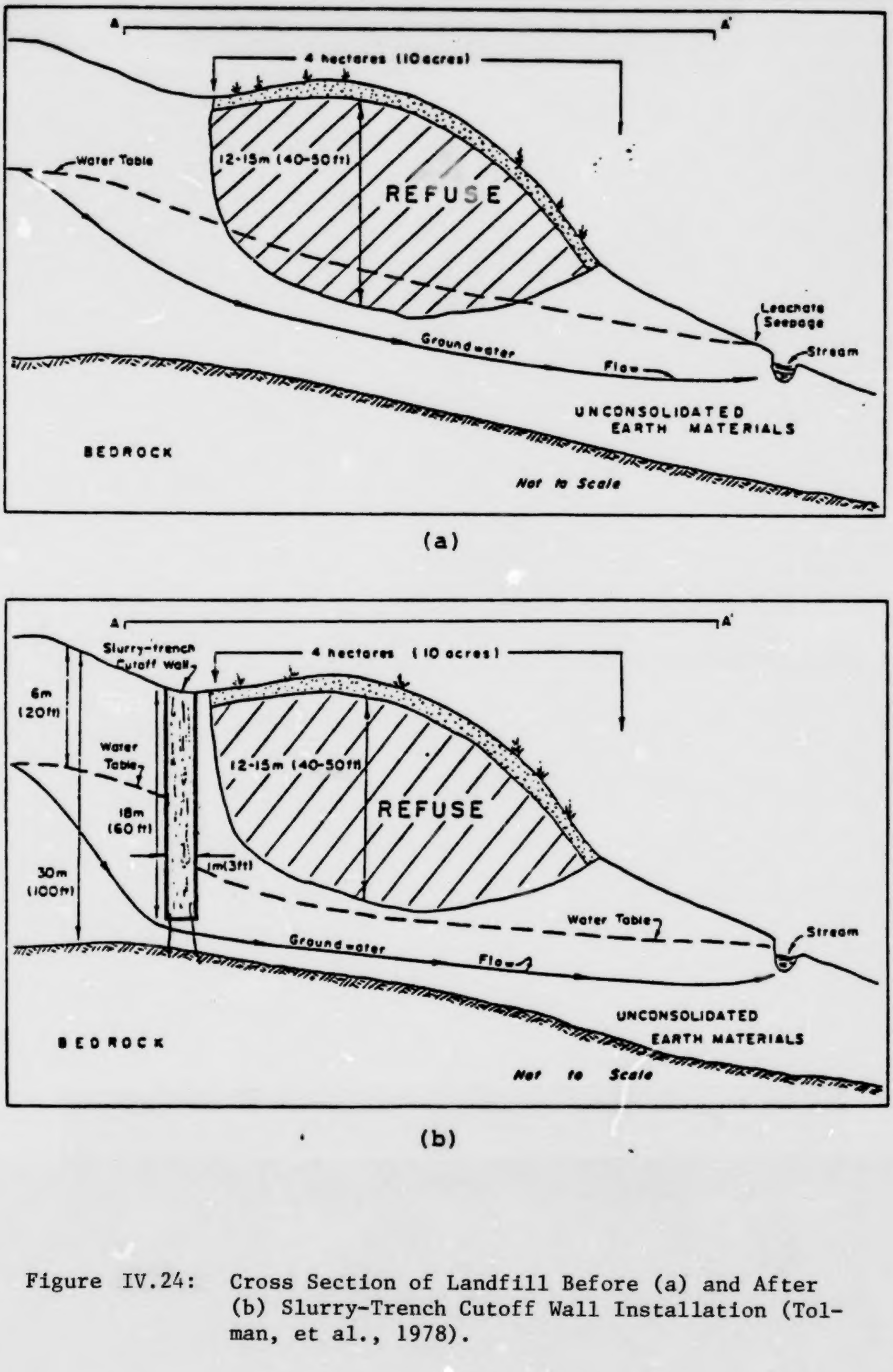

A
A'
4 hectares (10 acres)
Water Table
12-15m (40-50 ft)
REFUSE
Leachate Seepage
Stream
Groundwater
Flow
UNCONSOLIDATED EARTH MATERIALS
BEDROCK
Not to Scale
(a)
A
A'
Slurry-trench Cutoff Wall
4 hectares (10 acres)
6m (20ft)
Water Table
12-15m (40-50ft)
REFUSE
18m (60 ft)
1m(3ft)
30m (100ft)
Water Table
Stream
Ground-water
Flow
UNCONSOLIDATED EARTH MATERIALS
BEDROCK
Not to Scale
(b)

Figure IV.24: Cross Section of Landfill Before (a) and After (b) Slurry-Trench Cutoff Wall Installation (Tolman, et al., 1978).

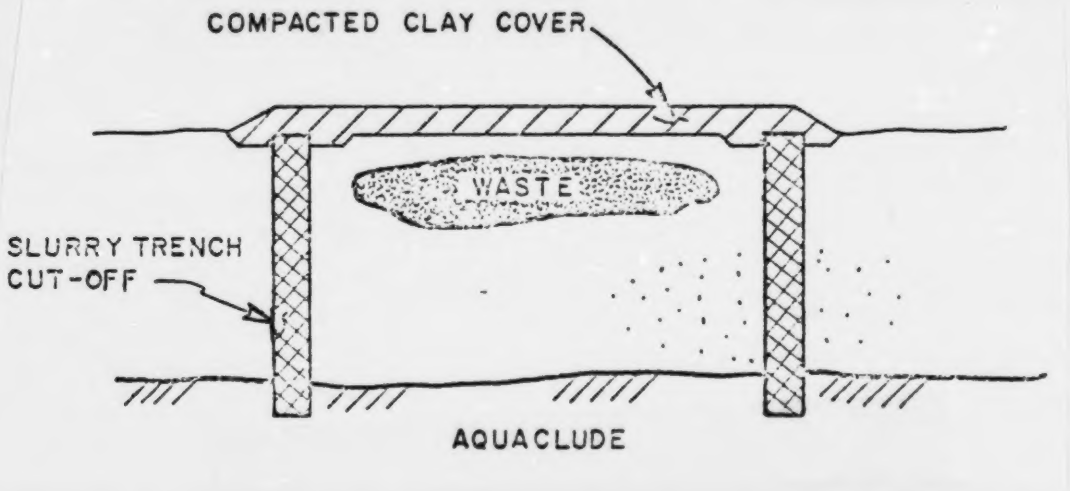

COMPACTED CLAY COVER
WASTE
SLURRY TRENCH CUT-OFF
AQUACLUDE

Figure IV.25: Isolation of Existing Buried Waste (Ryan, 1980).

trench can be solidified by backfilling with a mixture of bentonite and the excavated material, or it can be allowed to solidify itself by incorporating cement in the original slurry. The backfilled trench is usually called a soil-bentonite (S-B) trench, and the other method is called a cement-bentonite (C-B) trench. Comparative advantages of each method are outlined in Table IV.19 (Ryan, 1980).

Another method of slurry wall construction is the vibrating beam method. In this approach, a beam with a pressure hose attached is driven into the ground, then slurry is injected under pressure as the beam is gradually withdrawn. This is similar to grouting and possesses similar advantages/disadvantages. This approach can be more economical and can proceed faster than the trench method. However, the continuity of the wall cannot be guaranteed, the in-place thickness of the wall is considerably smaller, and the presence of boulders in the soil hinders this method more than the trench method.

Construction of slurry trenches is generally simple and consists only of excavating, recirculating the slurry, and backfilling. Excavation can be accomplished by any one or combinations of the following: backhoe; draglines; clamshells; bucket scrapers; or rotary drilling equipment. The choice of the specific type of excavation equipment is generally governed by the depth and width of excavation (Xanthakos, 1979). The backhoe is usually desirable when depths required are shallow. For depths of 30 meters or more, draglines are required. Because dragline bucket widths usually exceed 2 meters, they are not economical for C-B trenches due to high material costs.

Table IV.19: Comparison of C-B and S-B Slurry Trenches (Ryan, 1980).

Cement-Bentonite (C-B)	**Soil-Bentonite** (S-B)
1. Independent of availability or quality of soil for backfill.	1. Lower material costs
2. More suitable for limited access areas.	2. Can achieve higher permeability than C-B.
3. Cement sets quickly. Can cut trenches or allow traffic over wall in just a few days.	
4. Can be constructed in sections. S-B requires continuous trenching in one direction.	

Clamshells can be cable-mounted or, like the bucket scraper, mounted to a rigid sliding bar and used for deep trench excavation (Ryan, 1980).

Recirculation of the slurry is important for maintaining the integrity of the slurry. During excavation the slurry will be subjected to losses through seepage and changes in density through addition of excavated material. Control of these changes is achieved by continuously recirculating the slurry through a central mixing unit which may have provisions for separating excavated materials from the original slurry. Backfilling operations may require mixing of different soil types prior to placement in the trench. Mixing can be accomplished by discing and blading. The mixed soil is then bulldozed into the trench, partially mixing with and displacing the slurry. Backfilling follows trenching after an interval of time sufficient to prevent interference between the two activities.

An important final aspect of slurry trench construction is keying into an underlying impervious zone. Trenches will require 2 or 3 feet for keying into clay materials, and will require a grout connection when keying into impervious bedrock (D'Appolonia, no date).

Design

The important design considerations of any slurry-trench are the composition of the slurry and the ensuing impermeable wall. Design procedures for slurry walls range from general rules-of-thumb to detailed mathematical analyses of all aspects of the system. A general guideline approach is probably the most helpful.

D'Appolonia (no date) suggests that viscosities of both C-B and S-B slurries should be such that drain times from a Marsh Funnel range from 40 to 50 seconds. It is also recommended that the specific gravity of the slurry be at least 15 pounds per cubic foot less than the unit weight of the backfill. The permeability of the S-B backfill will depend on the soil and the amount of bentonite blended in. These characteristics are depicted in Figures IV.26 and IV.27. The ideal consistency for backfill placement is a paste having a water content slightly above the liquid limit of the sand-clay-bentonite backfill mix. This usually corresponds to a slump cone reading of 2 to 6 inches.

The durability of the slurry-trench refers to its resitance to attack from contaminants. In the presence of clean ground water, both C-B and S-B trenches show little deterioration and can be considered permanent. However, C-B trenches show poor performance records where acids or sulphates are present. Similarly, exposure of an S-B trench to certain contaminants can lead to increased permeability through pore fluid substitution or the increased solubility of barrier minerals in the contaminant fluid. Pore fluid substitution can be the result of high concentrations of salts, which attract the waters of hydration, or it can result from ion substitution within the clay matrix. Permeabilities of S-B trenches have been shown to increase in the presence of certain organics, calcium, magnesium, heavy metals and solutions of high ionic strength (D'Appolonia, no date).

Xanthakos (1979) suggests that a slurry system should be designed based on the functions of the slurry. These functions are:

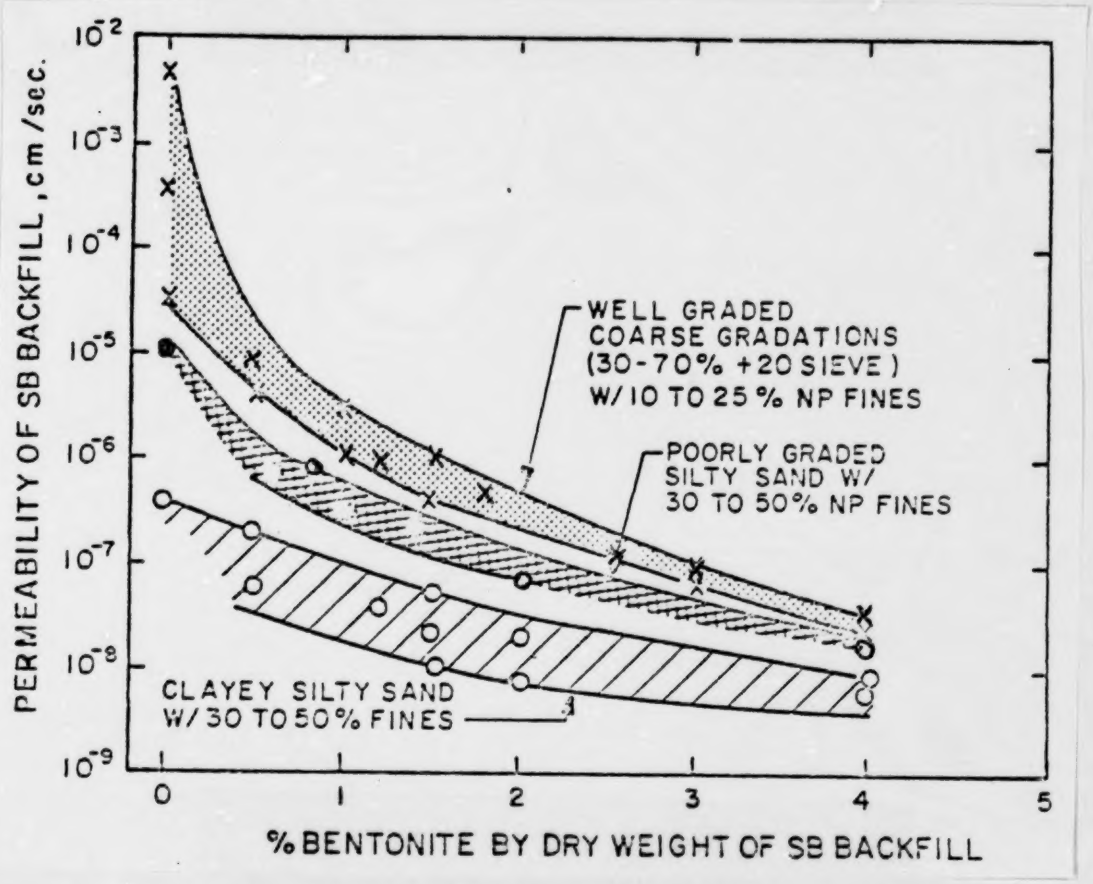


Figure IV.26: Relationship Between Permeability and Quantity of Bentonite Added to SB Backfill (Ryan, 1980).

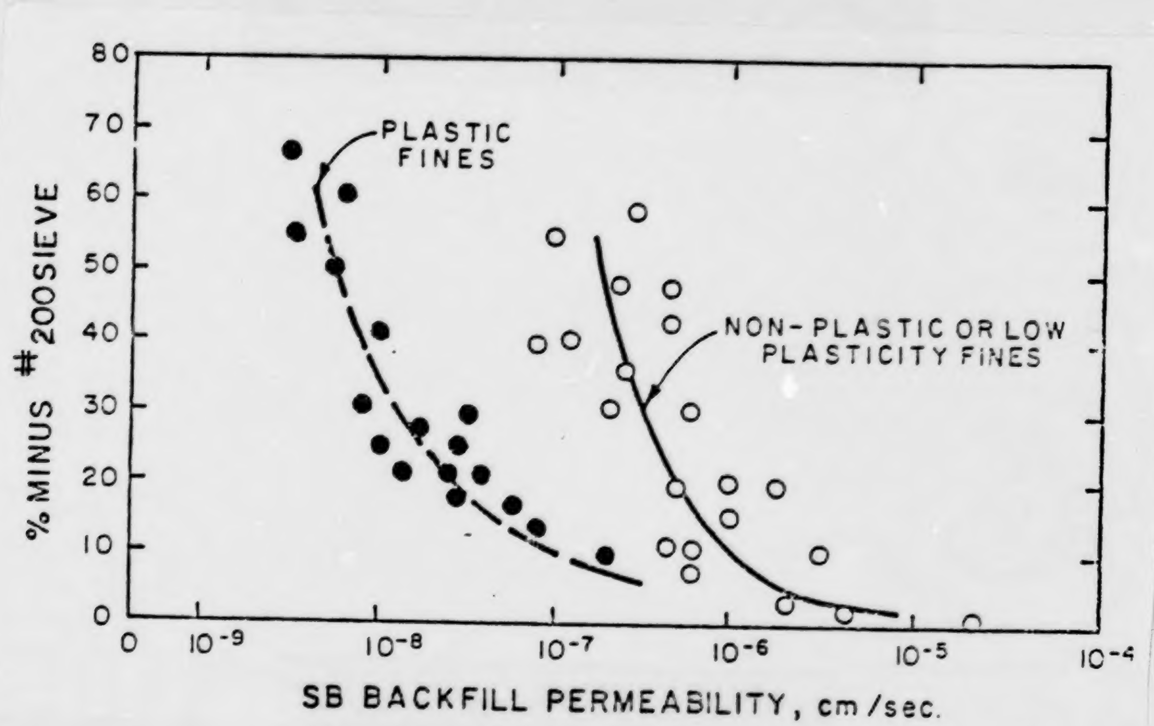


Figure IV.27: Permeability of Soil - Bentonite Backfill Related to Fines Content (Ryan, 1980).

(1) support the face of the excavation, and also prevent the soil from sloughing and peeling off;

(2) seal the formation and form the filter cake, preventing slurry loss to the ground;

(3) suspend detritus, thereby preventing sludgy unconsolidated layers from accumulating on the bottom of the trench; and

(4) carry the cuttings in the slurry volume, thereby preventing sedimentation in the mud circuit.

All of the above functions can be controlled by manipulating the physical properties of the slurry, i.e., density, viscosity, etc. Xanthakos (1979) has outlined a series of simple steps and procedures for proportioning the materials that comprise a slurry. These are as follows:

(1) Determine the density required for trench stability. The density can be controlled by the presence of colloid and non-colloid solid materials. If the depth to an impermeable formation (H) is known, the required slurry density can be calculated by the following (see Figure IV.28).

$$\gamma f = \frac{\gamma(1-m^2)K\alpha + \gamma^1 m^2 K\alpha + \gamma_w m^2}{n^2}$$

where

γf = required slurry density (gm/m^3)

γ = unit weight of soil (gm/m^3)

$K\alpha$ = tan^2 (45-θ^1/2)

m = natural ground water level as a fraction of total depth of excavation (H)

γw = unit weight of water (gm/m^3)

γ^1 = effective (buoyant) weight of soil (gm/m^3)

θ^1 = angle of shear resistance.

n = slurry level as a fraction of total depth of excavation (H)

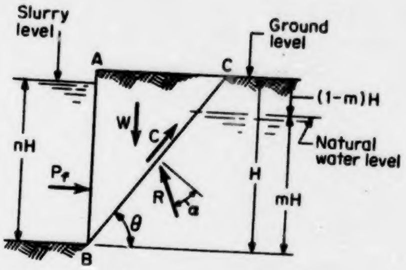

Slurry level
Ground level
A
C
B
(1-m)H
Natural water level
W
C
nH
P_f
R
α
θ
H
mH

Figure IV.28: Stability of a Trench for Arbitrary Slurry and Natural Water Level (Xanthakos, 1979).

(2) Select the funnel viscosity by reference to Table IV.20.

(3) Establish any applicable control limits from Table IV.21.

(4) Determine whether control agents (peptizers, polyelectrolytes, fluid-loss-control materials, etc.) are necessary and economically justified.

(5) Proportion the constituent materials (water, bentonite, control agents, and non-colloid solids). This phase merely consists of a quantitative estimation. The proportioning may be empirical and depend on experience if the properties of the materials selected are known, or it may have a technical basis of tests and estimations.

In general, slurry-trenches are attractive alternatives when an impervious natural barrier exists at a reasonable depth and the waste area is relatively large. A clayey sand or sandy clay containing 30 to 60% fines blended with the bentonite slurry is usually satisfactory for most waste isolation applications (D'Appolonia, no date).

Costs

Table IV.22 shows the comparative costs of S-B and C-B slurry walls.

Advantages and Disadvantages

There are many instances where slurry wall technologies have been employed. Slurry systems have been employed for their impermeability as cutoff and diaphragm walls, and slurries have been used to aid in the construction of load bearing elements and foundations (Xanthakos, 1979).

To date, there has been very little information provided on the performance of slurry walls applied to ground water pollution control problems. This does not mean the technology has not been applied. Slurry walls have been constructed at the Rocky Mountain Arsenal in

Table IV.20: Funnel Viscosity for Common Types of Soil (Xanthakos, 1979)

Type of Soil	Funnel Viscosity, s/946 cm^3	
	Excavation in Dry Soil	Excavation with Groundwater
Clay	27-32	
Silty sand, sandy clay	29-35	
Sand, with silt	32-37	38-43
Fine to coarse	38-43	41-47
And gravel	42-47	55-65
Gravel	46-52	60-70

Table IV.21: Control Limits for the Properties of Slurries (Xanthakos, 1979).

	Property							
Function	Average bentonite concentration,[†] %	Density, lb/ft^3	sp gr	Plastic viscosity, cP	Marsh cone viscosity	10-min gel strength (Fann), lb/100 ft^2	pH	Sand content, %
Face support	>3-4	>64.3	>1.03	....	Limits established by soil type	‡	....	>1§
Sealing process	>3-4	.....	.....	....		....	....	1
Suspension of detritus	>3-4	.....	.....	....		>12-15		
Displacement by concrete	<15	<78	<1.25	<20		....	<12	<25
Separation of noncolloids	.....	.....	.....	....		....	....	<30
Physical cleaning	<15	<78	<1.25	....		....	....	<25
Pumping of slurry	.....	.....	.....	....		Variable		
Limits	>3-4 <15	>64.3 <78	>1.03 <1.25	<20		>12-15	<12	>1 <25

*Controls are not considered necessary for apparent viscosity and yield stress. Whereas fluid loss commonly is judged by standard filtration test and a maximum film thickness of 2 mm, better control limits are established by stagnation-gradient tests.

[†] Should be expected to vary widely because of different bentonite brands.

‡The shear strength of filter cake is more applicable to peel-off control (also the time required for its formation).

§Optional.

Table IV.22: Approximate Slurry Wall Costs as a Function of Medium and Depth (Spooner, Wetzel and Grube, 1982)

SOIL TYPE	SOIL-BENTONITE WALL*			CEMENT-BENTONITE WALL*		
	DEPTH ≤30 FEET	DEPTH 30-75 FEET	DEPTH 75-120 FEET	DEPTH ≤60 FEET	DEPTH 60-150 FEET	DEPTH >150 FEET
SOFT TO MEDIUM SOIL N ≤40	2-4	4-8	8-10	15-20	20-30	30-75
HARD SOIL N 40-200	4-7	5-10	10-20	25-30	30-40	40-95
OCCASIONAL BOULDERS	4-8	5-8	8-25	20-30	30-40	40-85
SOFT TO MEDIUM ROCK N ≥200 SANDSTONE, SHALE	6-12	10-20	20-50	50-60	60-85	85-175
BOULDER STRATA	15-25	15-25	50-80	30-40	40-95	95-210
HARD ROCK GRANITE, GNEISS, SCHIST*	---	---	---	95-140	140-175	175-235

*NOMINAL PENETRATION ONLY

FOR STANDARD REINFORCEMENT IN SLURRY WALLS AND $8.99 PER SQ.FT.
FOR CONSTRUCTION IN URBAN ENVIRONMENT ADD 25% TO 50% OF PRICE

* In 1979 dollars per square foot.

Colorado and the Gilson Road Hazardous Waste Dump in New Hampshire. A list of the advantages/disadvantages of slurry-trenches compared to grouting, sheet piling, pumping or other techniques is shown in Table IV.23.

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Table IV.23: Advantages/Disadvantages of Slurry Trenches

Advantages	Disadvantages[(a)]
1. Construction methods are simple(a).	1. Cost of shipping bentonite from west.
2. Adjacent areas not affected by ground water drawdown(a).	2. Some construction procedures are patented and will require a license.
3. Bentonite (mineral) will not deteriorate with age(a).	3. In rocky ground, over-excavation is necessary because of boulders.
4. Leachate-resistant bentonites are available(a).	4. Bentonite deteriorates when exposed to high ionic strength leachates.
5. Low maintenance requirements(a).	
6. Eliminate risks due to pump breakdowns, or power failures(b).	
7. Eliminate headers and other above ground obstructions(b).	

(a) - Tolman, et al., 1978

(b) - Ryan, 1980

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SECTION V

TREATMENT OF GROUND WATER

Concepts for treatment of contaminated ground water following its pumpage from the subsurface are well established. These concepts have been developed from years of experience treating industrial wastewaters. However, confusion may occur when these concepts are applied to site specific contaminated ground waters. The type of treatment required depends primarily on the contaminants being removed. Treatment systems may be relatively simple when a single chemical is the only contaminant, or extremely complex for cases involving numerous contaminants. In most cases, treatability studies should be conducted with representative samples to determine appropriate treatment components. This section addresses air stripping, activated carbon, and biological treatment for organics in ground water, and chemical precipitation for inorganics in ground water. Due to the growing importance of the first two processes, Appendix C contains more detailed information on air stripping, and Appendix D does similarly for activated carbon adsorption.

AIR STRIPPING

Air stripping is a mass transfer process in which a substance in solution in water is transferred to solution in a gas. The rate of mass transfer depends upon several factors according to the following equation.

$$M = K_L \, a(C_L - C_g)$$

where:

M = mass of substance transferred per unit time and volume ($gm/hr/m^3$)

K_L = coefficient of mass transfer (m/hr)

a = effective area (m^2/m^3)

$(C_L - C_g)$ = driving force (concentration difference between liquid phase and gas phase, gm/m^3)

The driving force is an important aspect in the success or failure of an air stripping process. The driving force is the difference between actual conditions in the air stripping unit and conditions associated with equilibrium between the gas and liquid phases. If equilibrium exists at the air-liquid interface, the liquid phase concentration is related to the gas phase concentration by Henry's law which states:

$$C_{ig} = HC_{i\ell}$$

where

C_{ig} = equilibrium concentration in gas phase (gm/m^3)

$C_{i\ell}$ = equilibrium concentration in liquid phase (gm/m^3)

H = Henry's law constant

another form of Henry's law is

$$P_A = H'C$$

where

P_A = partial pressure of substance in the air mixture in contact with the water at equilibrium (atm.)

H' = Henry's law constant ($atm./gm/m^3$)

C = concentration of substance in the water at equilibrium (gm/m^3)

The Henry's law constant can be used to predict the strippability of a chemical. A compound with a high Henry's law constant generally is more easily stripped from water than one with a lower Henry's law constant.

The mass of a contaminant that can be transferred not only is a function of the driving force, but is also a function of the mass transfer. Due to the difficulty in separating these two parameters, they are usually evaluated as one coefficient, K_La. The coefficient K_La is a function of the geometry and physical characteristics of the air stripping equipment, the loading rate (air-to-water ratio), and the temperature. These are factors that must be considered in the design of an air stripping process.

Description of Process

As shown in Figure V.1, there are four basic equipment configurations used for air stripping, including diffused aeration, counter-current packed columns, cross-flow towers, and coke tray aerators. Diffused aeration stripping uses aeration basins similar to standard wastewater treatment aeration basins. Water flows through the basin from top to bottom with the air dispersed through diffusers at the bottom of the basin. The air-to-water ratio is significantly lower than in either the packed column or the cross-flow tower.

In the counter-current packed column, water containing one or more impurities is allowed to flow down through a column containing packing material with air flow counter-currently up through the column. In this way the contaminated water comes into intimate contact with clean air. Packing materials are used which provide high-void volumes and high-surface area. In the cross-flow tower, water flows down through the packing as in the counter-current packed column, however, the air is pulled across the water flow path by a fan. The coke tray aerator is a

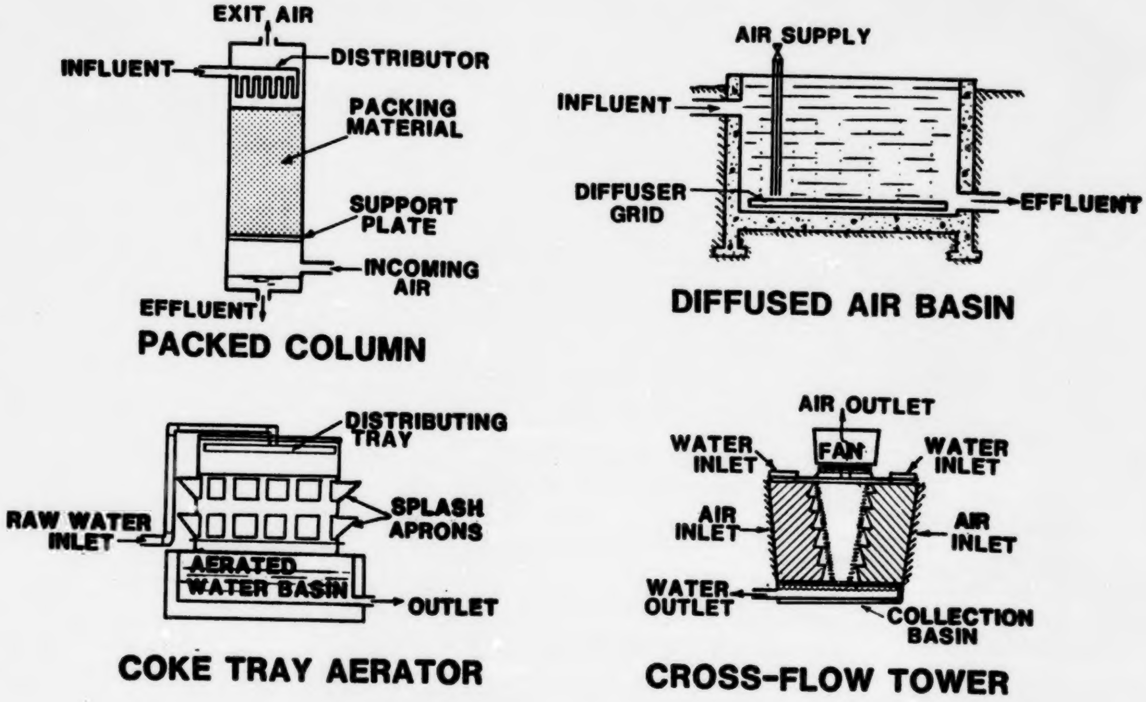

EXIT AIR
INFLUENT
DISTRIBUTOR
PACKING MATERIAL
SUPPORT PLATE
INCOMING AIR
EFFLUENT
PACKED COLUMN
AIR SUPPLY
INFLUENT
DIFFUSER GRID
EFFLUENT
DIFFUSED AIR BASIN
DISTRIBUTING TRAY
SPLASH APRONS
RAW WATER INLET
AERATED WATER BASIN
OUTLET
COKE TRAY AERATOR
AIR OUTLET
FAN
WATER INLET
WATER INLET
AIR INLET
AIR INLET
WATER OUTLET
COLLECTION BASIN
CROSS-FLOW TOWER

Figure V.1: Air Stripping Equipment Configurations

simple, low-maintenance process. The water being treated is allowed to trickle through several layers of trays. This produces a large surface area for gas transfer.

The counter-current packed tower appears to be the most appropriate equipment configuration for treating contaminated ground waters for the following reasons:

1. It provides the most liquid interfacial area.
2. High air-to-water volume ratios are possible due to the low air pressure drop through the tower.
3. Emission of stripped organics to the atmosphere may be environmentally unacceptable; however, a counter-current tower is relatively small and can be readily connected to vapor recovery equipment.

Design Parameters and Procedures

The design of an air stripping process for stripping volatile organics from contaminated ground water is accomplished in two steps. The cross-sectional area of the column is determined and then the height of the packing is determined. The cross-sectional area of the column is determined by using the physical properties of the air flowing through the column, the characteristics of the packing, and the air-to-water flow ratio. A key factor is the establishment of an acceptable air velocity. A general rule of thumb used for establishing the air velocity is that an acceptable air velocity is 60% of the air velocity at flooding. Flooding is the condition in which the air velocity is so high that it holds up the water in the column to the point where the water becomes the continuous phase rather than the air. If the air-to-water ratio is held constant, the air velocity determines the flooding condition. For a selected air-to-water ratio, the cross-sectional area is determined by dividing the air flow rate by the air velocity. The selection of the design air-to-water ratio must be based upon experience or pilot-scale treatability studies. Treatability studies are particularly important for developing design information for contaminated ground water.

The height of column packing may be determined by the following equation:

$$Z = \frac{\ell n \left[\frac{(X_2 - Y_1/H)}{(X_1 - Y_1/H)} (1-A) + A \right] L}{K_La \; C \; (1-A) \; (1-X) \; M}$$

where

Z = height of packing, feet

L = water velocity, lb moles/hr/ft^2

X_2 = influent concentration of pollutant in ground water, mole fraction

X_1 = effluent concentration of pollutant in ground water, mole fraction

K_La = mass transfer coefficient, 1/hr

C = molar density of water = 3.47 lb mole/ft^3

H = Henry's law constant, mole fraction in air per mole fraction in water

G = air velocity, lb mole/hr/ft^2

$A = \frac{L}{HG}$

$(1-X)M$ = the average of one minus the equilibrium water concentration through the column

Y_1 = influent concentration of pollutant in air, mole fraction

In most cases, the following assumptions can be made:

(1) $Y_1 = 0$, there should be no pollutants in the influent air.

(2) $(1-X)M = 1$, the influent concentrations should be too small when converted to mole fraction to shift this term significantly from 1.0.

The equation for determining the column packing height is then reduced to:

$$Z = \frac{n \left[\frac{X_2}{X_1} (1-A) + A \right] L}{K_L a \; C \; (1-A)}$$

All variables except the mass transfer coefficient are set by the design conditions. The selection of a suitable mass transfer coefficient must be based upon pilot scale treatability studies and the judgment of the design engineer. The mass transfer coefficient is a function of:

(1) Type of volatile organic to be removed

(2) Air-to-water ratio

(3) Temperature of the ground water

(4) Type of packing

(5) Geometry of the tower

A plot of experimental data as shown in Figure V.2 can be helpful in selecting the proper mass transfer coefficient.

Applications to Ground Water

Air stripping has been successfully used for removing volatile organics from contaminated ground waters. These successful operations include an industrial park investigated by Stover (1982), a case study reported by Pekin and Moore (1982), and Rockaway Township, New Jersey, reported by McKinnon and Dyksen (1982). A summary of the removals achieved in these operations for various organic contaminants at various air-to-water ratios is given in Table V.1.

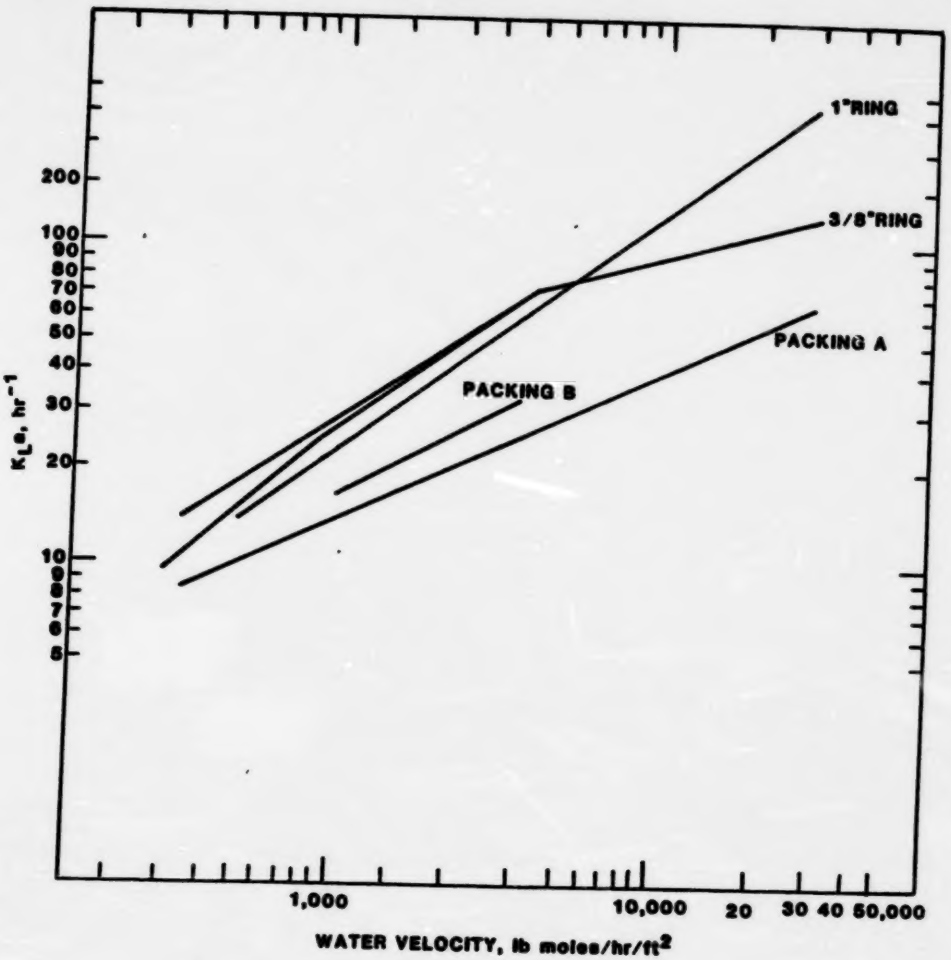


Figure V.2: Mass Transfer Coefficients as a Function of Water Velocity

Table V.1: Packed Column Air Stripping of Volatile Organics

Organic Contaminant	Air:Water Ratio	Influent µg/ℓ	Effluent µg/ℓ
1,1,2-Trichloroethylene	9.3	80	16
	96.3	80	3
	27.0	75	16
	156.0	813	52
	44.0	218	40
	75.0	204	36
	125.0	204	27
1,1,1-Trichloroethane	9.3	1200	460
	96.3	1200	49
	27.0	90	31
	156.0	1332	143
1,1-Dichlorethane	9.3	35	9
	96.3	35	1
1,2-Dichloropropane	27.0	50	<5
	146.0	70	<5
	156.0	377	52
Chloroform	27.0	50	<2
	146.0	57	<2
Diisopropyl ether	44.0	15	7
	75.0	14	6
	125.0	4	4

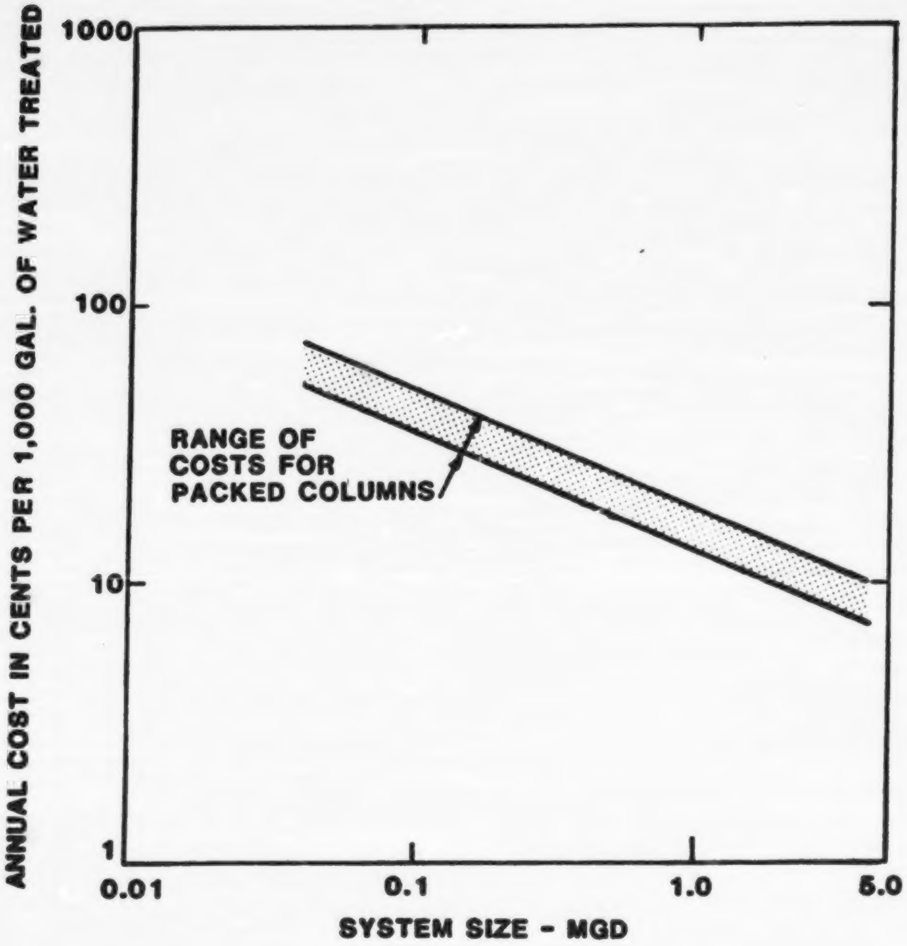
It has been pointed out that temperature has an effect on the mass transfer coefficient. This becomes important when the contaminated ground water contains compounds that are very soluble. This makes their removal by ambient temperature air stripping almost impossible. Lamarre, McGarry, and Stover (1983) have reported on such a case. It was found in methyl ethyl ketone removal, that at 54°F and an air-to-water ratio of 490, only 43% removal occurred; at 90°F and an air-to-water ratio of 513, removal was 92%; and at 136°F and an air-to-water ratio of 469, the removal was 99%. Removal efficiency increased dramatically with temperature and less sharply with the air-to-water ratio. Therefore, high temperature air-stripping, or steam stripping, should be investigated for each case encountered.

Costs

Although the variation in the design of packed column air stripping systems results in various costs, the major components of an air stripping system for removing organic contaminants from a ground water would include the packed column, the air supply equipment, and re-pumping. Annual costs per 1,000 gallons of water treated has been presented by Dyksen, et al. (1982), and Figure V.3 provides a summary. The costs are 1982 costs and are based upon preliminary designs for achieving 90 percent removal of trichloroethylene (TCE).

CARBON ADSORPTION

Adsorption occurs when an organic molecule is brought to the activated carbon surface and held there by physical and/or chemical forces. The quantity of a compound or group of compounds that can be



NOTES:

1. ANNUAL COSTS INCLUDES AMORTIZED CAPITAL COSTS AND ANNUAL OPERATING COSTS
2. SYSTEM SIZE REPRESENTS AVERAGE PLANT CAPACITY.
3. RANGE OF COSTS FOR PACKED COLUMN ACCOUNTS FOR DIFFERENCES IN MATERIALS OF CONSTRUCTION AS DISCRIBED IN THE TEXT

Figure V.3: Comparison of Costs for Packed Column Aeration (Dyksen, et al., 1982)

adsorbed by activated carbon is determined by a balance between the forces that keep the compound in solution and the forces that attract the compound to the carbon surface. Factors that affect this balance include:

(1) Adsorptivity increases with decreasing solubility.

(2) The pH of the water can affect the adsorptive capacity. Organic acids adsorb better under acidic conditions, whereas amino compounds favor alkaline conditions.

(3) Aromatic and halogenated compounds adsorb better than aliphatic compounds.

(4) Adsorption capacity decreases with increasing temperature although the rate of adsorption may increase.

(5) The character of the adsorbent surface has a major affect on adsorption capacity and rate. The raw materials and the process used to activate the carbon determine its capacity.

When activated carbon particles are placed in water containing organic chemicals and mixed to give adequate contact, the adsorption of the organic chemicals occurs. The organic chemical concentration will decrease from an initial concentration, C_o, to an equilibrium concentration, C_e. By conducting a series of adsorption tests, it is usually possible to obtain a relationship between the equilibrium concentration and the amount of organics adsorbed per unit mass of activated carbon.

The Freundlich isotherm and the Langmuir isotherm are most often used to represent the adsorption equilibrium. One form of the Freundlich isotherm is:

$$\frac{X}{m} = KC_e^{1/n}$$

where

X = mass of organic adsorbed (gm)

m = mass of activated carbon (gm)

C_e = equilibrium concentration of organics (gm/m^3)

K, n = experimental constants

The Langmuir isotherm has the following form:

$$\frac{X}{m} = \frac{a\ K\ C_e}{1 + K\ C_e}$$

where

a = mass of adsorbed organic required to completely saturate a unit mass of carbon (gm)

K = experimental constant

From an isotherm test it can be determined whether or not a particular organic material can be removed effectively. It will also show the approximate capacity of the carbon for the application, and provide a rough estimate of the carbon dosage required. Isotherm tests also afford a convenient means of studying the effects of pH and temperature on adsorption. Isotherms put a large amount of data into concise form for ready evaluation and interpretation. Isotherms obtained under identical conditions using the same contaminated ground water for two or more carbons can be quickly and conveniently compared to determine the relative merits of the carbons.

Figure V.4 represents a typical Freundlich isotherm for the comparison of two carbons removing the organics from a contaminated ground water. The isotherm for carbon A is at a high level and has only a slight slope. This means that adsorption is large over the entire range studied. The isotherm for carbon B is at a lower range and with a steeper slope. This means lower adsorption than carbon A. However,

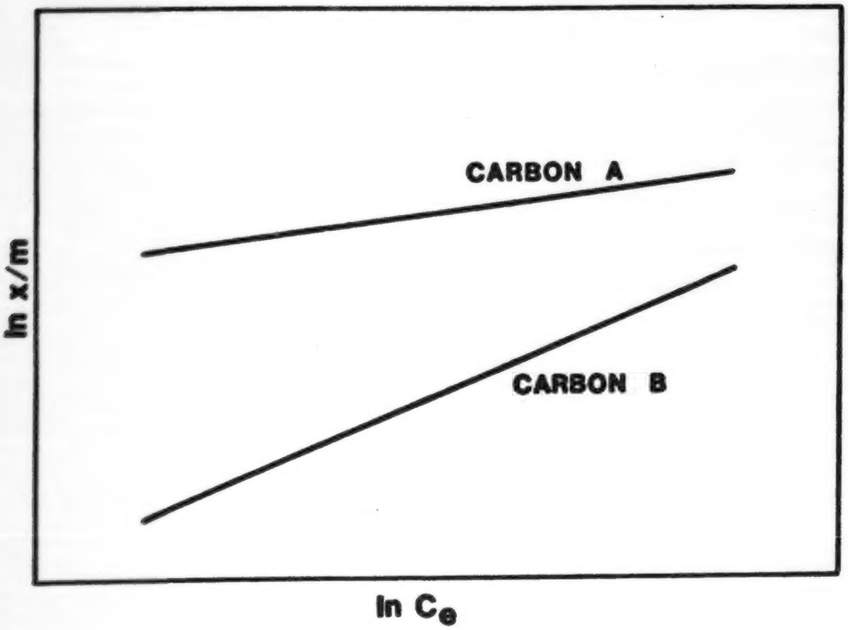


Figure V.4: Adsorption Isotherm

adsorption improves at higher concentrations. In general, the steeper the slope of its isotherm, the greater the efficiency of a carbon in column operation.

Description of Process

Activated carbon adsorption may be accomplished by batch, column, or fluidized-bed operations. The usual contacting systems are fixed bed or countercurrent moving beds. The fixed beds may employ downflow or upflow of water. The countercurrent moving beds employ upflow of the water and downflow of the carbon since the carbon can be moved by the force of gravity. Both fixed beds and moving beds may use gravity or pressure flow.

Figure V.5 shows a typical fixed-bed carbon column employing a single column with downflow of the water. The column is similar to a pressure filter and has an inlet distributor, an underdrain system, and a surface wash. During the adsorption cycle the influent flow enters through the inlet distributor at the top of the column, and the ground water flows downward through the bed and leaves through the underdrain system. The unit hydraulic flow rate is usually from 2 to 5 gpm/ft^2. When the head loss becomes excessive due to the accumulated suspended solids, the column is taken off-line and backwashed.

Figure V.6 shows a typical countercurrent moving-bed carbon column employing upflow of the water. Two or more columns are usually provided and are operated in series. The influent contaminated ground water enters the bottom of the first column by means of a manifold system which uniformly distributes the flow across the bottom. The

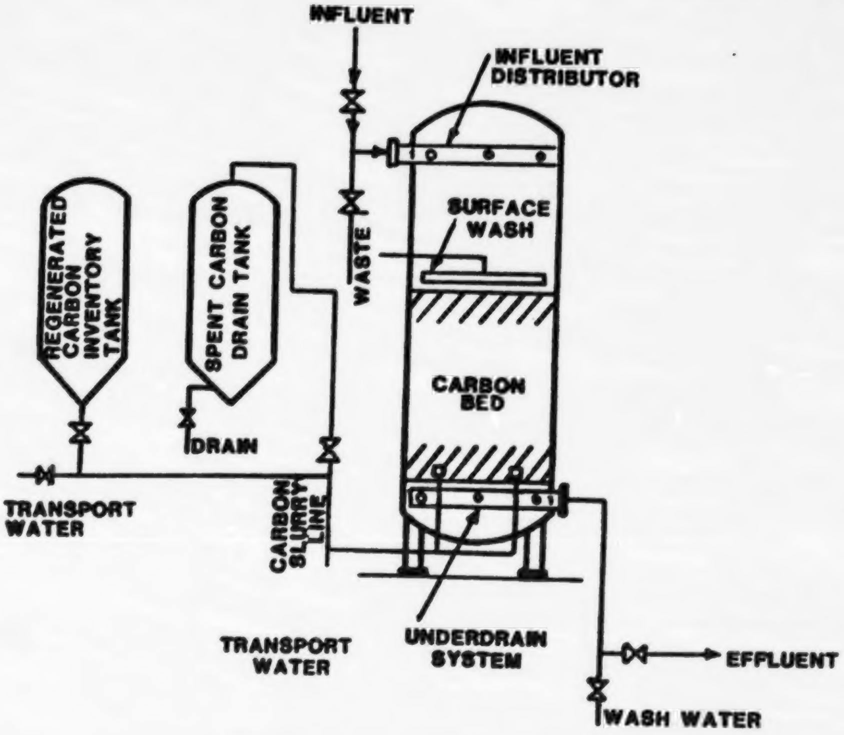

INFLUENT
INFLUENT DISTRIBUTOR
REGENERATED CARBON INVENTORY TANK
SPENT CARBON DRAIN TANK
SURFACE WASH
WASTE
CARBON BED
DRAIN
TRANSPORT WATER
CARBON SLURRY LINE
TRANSPORT WATER
UNDERDRAIN SYSTEM
EFFLUENT
WASH WATER

Figure V.5: Fixed-Bed Adsorption System

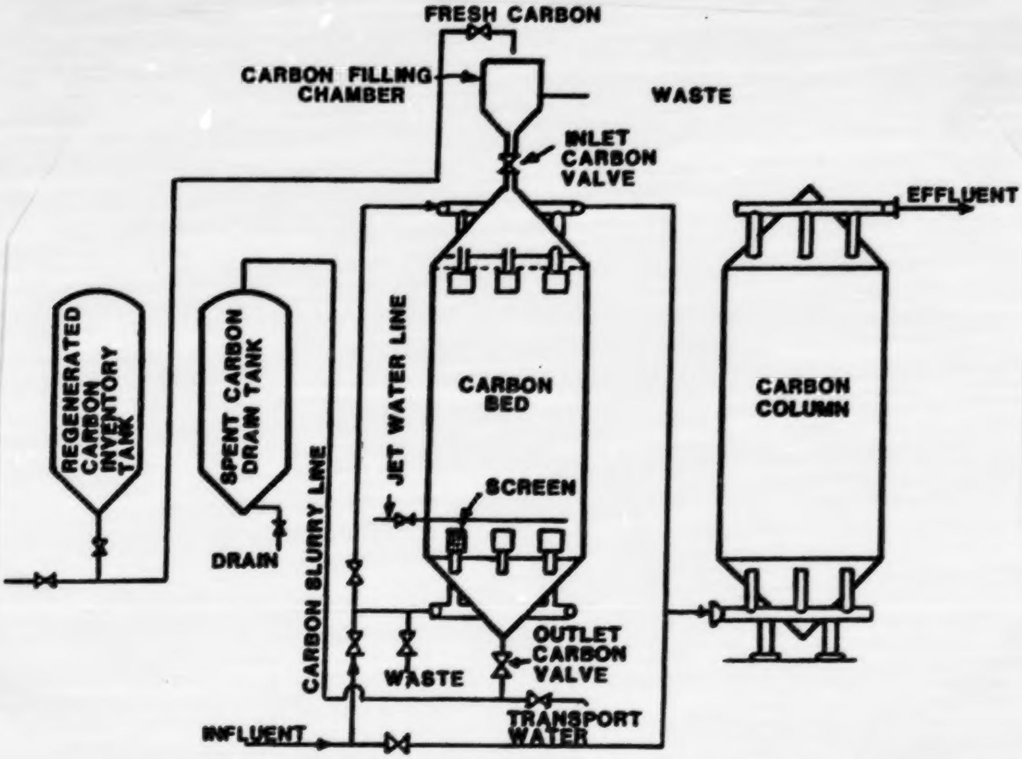

FRESH CARBON
CARBON FILLING CHAMBER
WASTE
INLET CARBON VALVE
EFFLUENT
REGENERATED CARBON INVENTORY TANK
SPENT CARBON DRAIN TANK
JET WATER LINE
CARBON BED
CARBON COLUMN
SCREEN
DRAIN
CARBON SLURRY LINE
OUTLET CARBON VALVE
WASTE
TRANSPORT WATER
INFLUENT

Figure V.6: Moving-Bed Adsorption System

ground water flows upward through the column. The unit hydraulic flow rate is usually 2 to 10 gpm/ft^2. The effluent is collected by a screen and manifold system at the top of the column and flows to the bottom manifold of the second column. The carbon flow is not continuous but instead is pulse-wise.

The fluidized bed consists of a bed of activated carbon. The water flows upward through the bed in the vertical direction. The upward liquid velocity is sufficient to suspend the activated carbon so that the carbon does not have constant interparticle contact. At the top of the carbon there is a distinct interface between the carbon and the effluent water. The principal advantage of the fluidized bed is that waters with appreciable suspended solids content may be given adsorption treatment without clogging the bed, since the suspended solids pass through the bed and leave with the effluent. This should not be a concern with ground waters.

Design Parameters and Procedures

Although the treatability of a particular wastewater by carbon and the relative capacity of different types of carbon for treatment may be estimated from adsorption isotherms, carbon performance and design criteria are best determined by pilot column tests. Design-related information which can be obtained from pilot tests includes:

(1) Contact time

(2) Bed depth

(3) Pretreatment requirements

(4) Breakthrough characteristics

(5) Headloss characteristics

(6) Carbon dosage in pounds of pollutants removed per pound of carbon.

The design of an activated carbon adsorption column can be accomplished by using a kinetic equation which is based on a derivation by Thomas (1948). The method requires data obtained from a breakthrough curve. A typical breakthrough curve obtained from a pilot test is shown in Figure V.7. The expression by Thomas for an adsorption column is as follows:

$$\frac{C_o}{C} = 1 + \exp \frac{K_1}{Q} (A_oM - C_oV)$$

where

C = effluent pollutant concentration (gm/m^3)

C_o = influent pollutant concentration (gm/m^3)

K_1 = rate constant m^3 per day per gm

Q = flow rate, m^3 per day

A_o = adsorption capacity, gm per gm

M = mass of carbon, gm

V = throughput volume, m^3

Rearranging and taking the logarithms of both sides yields

$$\ln \left(\frac{C_o}{C} - 1\right) = \frac{K_1 \; A_oM}{Q} - \frac{K_1C_oV}{Q}$$

This is the equation of a straight line in which $\frac{K_1 \; A_oM}{Q}$ is the y-intercept and $\frac{K_1 \; C_o}{Q}$ is the slope of the line. The pilot column tests provides all parameters except K_1 and A_o. If $\ln (\frac{C_o}{C} - 1)$, is plotted versus V, the values of K_1 and A_o can be determined by a graphical solution. Then the mass of carbon needed for a selected breakthrough volume may be determined.

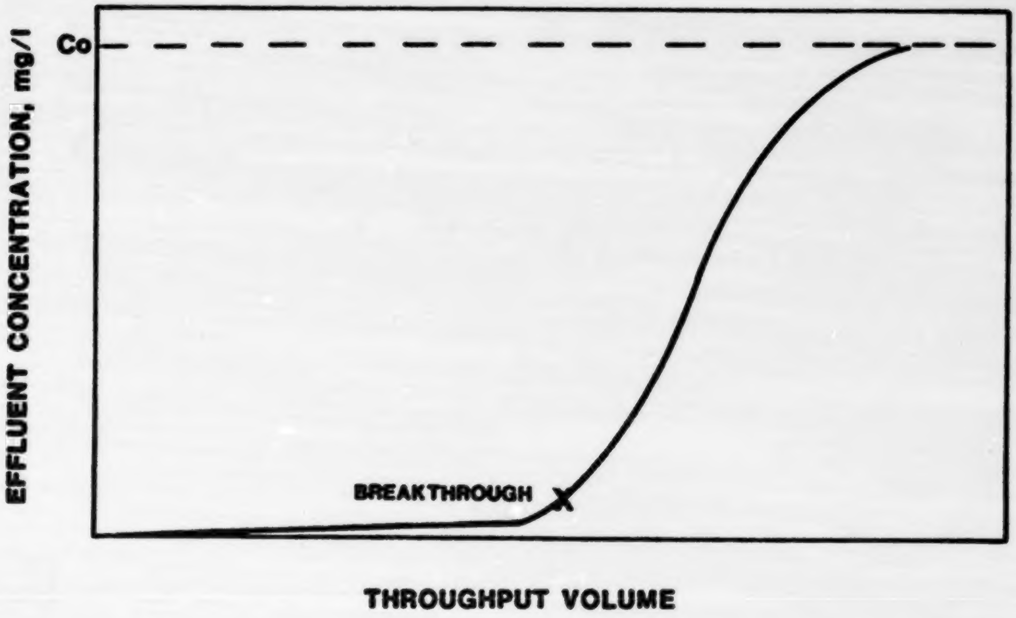


Figure V.7: Typical Breakthrough Curve

Applications to Ground Water

Activated carbon adsorption has been successfully used for removing organics from contaminated ground waters. Kaufman (1982) reported on 17 separate cases. The aquifers had been contaminated by leachate from lagoons or dumpsites, industrial accidents, and chemical spills due to railroad or truck accidents. Activated carbon successfully treated these contaminated aquifers. McDougall, Fusco, and O'Brien (1980) reported on the successful treatment of the Love Canal landfill leachate by activated carbon adsorption. O'Brien and Fisher (1983) have reported on 31 separate cases where activated carbon adsorption has been successful in treating contaminated ground waters. The reasons for treatment were to prevent the spread of contamination through an aquifer, for process water reuse, and for decontamination of potable water. Table V.2 provides some results obtained in these operations. In all cases, the activated carbon was very successful in removing priority pollutants.

Costs

The cost of treating ground water by activated carbon adsorption is dependent on a number of factors such as: flow rates, concentrations, type of contaminant; type of application; and site requirements. These factors determine equipment and carbon usage; thus it is difficult to be specific on costs. However, Kaufmann (1982) reported that for municipal potable treatment the costs have been in the \$0.40 to \$1.00 per person per month range. O'Brien and Fisher (1983) have reported that if the influent concentration is in the mg/ℓ range the costs have ranged from

Table V.2: Activated Carbon Adsorption of Organics

Contaminants	Influent concentration μg/ℓ	Effluent Concentration μg/ℓ
Phenol	63,000	<100
	2,400	< 10
	40,000	< 10
Carbon tetrachloride	61,000	< 10
	130,000	< 1
	73,000	< 1
1,1,2- Tetrachloroethane	80,000	< 10
Tetrachloroethylene	44,000	12
	70,000	< 1
1,1,1-Trichloroethane	23,000	N.D.
	1,000	< 1
	3,300	< 1
	12,000	< 5
	143,000	< 1
	115	< 1
Benzene	2,800	< 10
	400	< 1
	11,000	<100
2,4- Dichlorophenol	5,100	N.D.

N.D. - Nondetectable

$0.48 to $2.52 per 1000 gallons treated. However, if the influent concentrations are in the μg/ℓ range, the costs have varied from $0.22 to $0.55 per 1000 gallons treated.

BIOLOGICAL TREATMENT

In biological treatment of contaminated ground water, the objective is to remove or reduce the concentration of organic and inorganic compounds. Because many of the compounds that may be present in contaminated ground water are toxic to microorganisms, pretreatment of the ground water may be required. When a ground water containing organic compounds is contacted with microorganisms, the organic material is removed by the microorganisms through metabolic processes. The organic compounds may be used by the microorganisms to form new cellular material or to produce energy that is required by the microorganisms for their life systems. It has been found by Tabak, et al. (1981) and Kincannon and Stover (1981a, b, c, no date); Kincannon, Stover and Chung (1981); and Kincannon, et al. (1981; 1982a,b) that many organic compounds that are considered to be toxic are biodegraded by microorganisms when the proper environment is provided.

Heterotrophic microorganisms are the most common group of microorganisms providing the metabolic process for removing organic compounds from contaminated ground water. Heterotrophs use the same substances as sources of carbon and energy. A portion of the organic material is oxidized to provide energy while the remaining portion is used as building blocks for cellular synthesis. Three general methods exist by which heterotrophic microorganisms can obtain energy. These are fermentation, aerobic respiration, and anaerobic respiration.

In the case of fermentation, the carbon and energy source is broken down by a series of enzyme-mediated reactions which do not involve an electron transport chain. In aerobic respiration, the carbon and energy source is broken down by a series of enzyme-mediated reactions in which oxygen serves as an external electron acceptor. In anaerobic respiration, the carbon and energy source is broken down by a series of enzyme-mediated reactions in which sulfates, nitrates, and carbon dioxide serves as the external electron acceptors. The three processes of obtaining energy forms the basis for the various biological waste water treatment processes.

Description of Process

Biological treatment processes are typically divided into two categories; suspended growth systems and fixed-film systems. Suspended growth systems are more commonly referred to as activated sludge processes, of which several variations and modifications exist. The basic system consists of a large basin into which the contaminated water is introduced, and air or oxygen is introduced by either diffused aeration or mechanical aeration devices. The microorganisms are present in the aeration basin as suspended material. After the microorganisms remove the organic material from the contaminated water they must be separated from the liquid stream. This is accomplished by gravity settling. After separating the biomass from the liquid, the biomass increase resulting from synthesis is wasted and the remainder returned to the aeration tank. Thus, a relatively constant mass of microorganisms is maintained in the system. The performance of the process depends on the recycle of sufficient biomass. If biomass separation and concentration fails the entire process fails. The process requires the skills of well-trained operators.

Fixed-film biological processes differ from suspended growth systems in that microorganisms attach themselves to a medium which provides an inert support. Biological towers (trickling filters) and rotating biological contactors are the most common forms of fixed-film processes. The original trickling filter consisted of a bed of rocks over which the contaminated water was sprayed. The microbes, forming a slime layer on the rocks, would metabolize the organics, with oxygen being provided as air moved counter current from the water flow. A major drawback to the rock-bed trickling filter was the inefficient use of space and poor oxygen transfer.

Biological towers are a modification of the trickling filter. The media, which is comprised of polyvinyl chloride (PVC), polyethylene, polystyrene, or redwood is stacked into towers which typically reach 16 to 20 feet high. The contaminated water is sprayed across the top and, as it moves downward, air is pulled upward through the tower. A slime layer of microorganisms forms on the media and removes the organic contaminants as the water flows over the slime layer.

A Rotating Biological Contactor (RBC) consists of a series of rotating discs, connected by a shaft, set in a basin or trough. The contaminated water passes through the basin where the microorganisms, attached to the discs, metabolize the organics present in the water.

Approximately 40 percent of the disc's surface area is submerged. This allows the slime layer to alternately come in contact with the contaminated water and the air where oxygen is provided to the microorganisms.

Removal efficiencies are generally the same for fixed-film and suspended growth processes. However, fixed-film processes have the potential to be lower in cost, due to the absence of aeration equipment, and are easier to operate. Both systems may be operated under anaerobic conditions, which may offer advantages for certain contaminated waters.

Design Parameters and Procedures

The design of biological treatment processes is usually accomplished by using some type of kinetic model. The most widely used models have been developed by Eckenfelder, McKinney, Lawrence and McCarty, and Gaudy. However, Kincannon and Stover (no date) have found that a great amount of variability exists in the biokinetic constants for these models, and concluded that these models were not ideal for waters containing priority pollutants; therefore, they have developed the following models that are reliable for these types of waters:

Activated Sludge

$$V = \frac{FS_i/X}{\dfrac{U_{max}\ S_i}{S_i - S_e} - K_B}$$

Biological Tower and Rotating Biological Contactor

$$A = \frac{FS_i}{\dfrac{U_{max}\ S_i}{S_i - S_e} - K_B}$$

where

V = volume of aeration tank (m^3)

F = flow rate (m^3/day)

X = mixed liquor volatile solids (mg/l)

S_i = influent BOD, COD, TOC, or specific organics (mg/l)

S_e = effluent BOD, COD, TOC, or specific organics (mg/l)

U_{max} and K_B = biokinetic constants (day^{-1})

A = surface area of biological tower or rotating biological contactor (m^2)

The biokinetic constants are determined by conducting laboratory or pilot plant studies. After the biokinetic constants are determined, the required volume of aeration tank or the required surface area for a biological tower or rotating biological contactor can be determined for any flow rate; influent concentration of BOD, COD, TOC, or specific organic, and a required effluent concentration of BOD, COD, TOC, or specific organic.

Applications to Ground Water

Biological treatment of contaminated ground water has not been actively employed in the past. However, pilot plant studies by Kincannon and Stover (1983) showed that biological treatment of a contaminated ground water was feasible. In addition, Kincannon and Stover (no date) have conducted extensive research on the fate of priority pollutants in activated sludge treatment systems. The removal mechanisms of 24 priority pollutants are shown in Table V.3. It is seen that a majority of the 24 organic priority pollutants are removable by biological treatment. Figure V.8 shows the effluent phenol

Table V.3: Removal Mechanisms of Toxic Organics

Compound	Percent Treatment Achieved		
	Stripping	Sorption	Biological
Nitrogen Compounds			
Acrylonitrile	--	--	99.9
Phenols			
Phenol	--	--	99.9
2,4-DNP	--	--	99.3
2,4-DCP	--	--	95.2
PCP	--	0.58	97.3
Aromatics			
1,2-DCB	21.7	--	78.2
1,3-DCB	--	--	--
Nitrobenzene	--	--	97.8
Benzene	2.0	--	97.9
Toluene	5.1	0.02	94.9
Ethylbenzene	5.2	0.19	94.6
Halogenated Hydrocarbons			
Methylene Chloride	8.0	--	91.7
1,2-DCE	99.5	0.50	--
1,1,1-TCE	100.0	--	--
1,1,2,2-TCE	93.5	--	--
1,2-DCP	99.9	--	--
TCE	65.1	0.83	33.8
Chloroform	19.0	1.19	78.7
Carbon Tetrachloride	33.0	1.38	64.9
Oxygenated Compounds			
Acrolein	--	--	99.9
Polynuclear Aromatics			
Phenanthrene	--	--	98.2
Naphthalene	--	--	98.6
Phthalates			
Bis(2-Ethylhexyl)	--	--	76.9
Other			
Ethyl Acetate	1.0	--	98.8

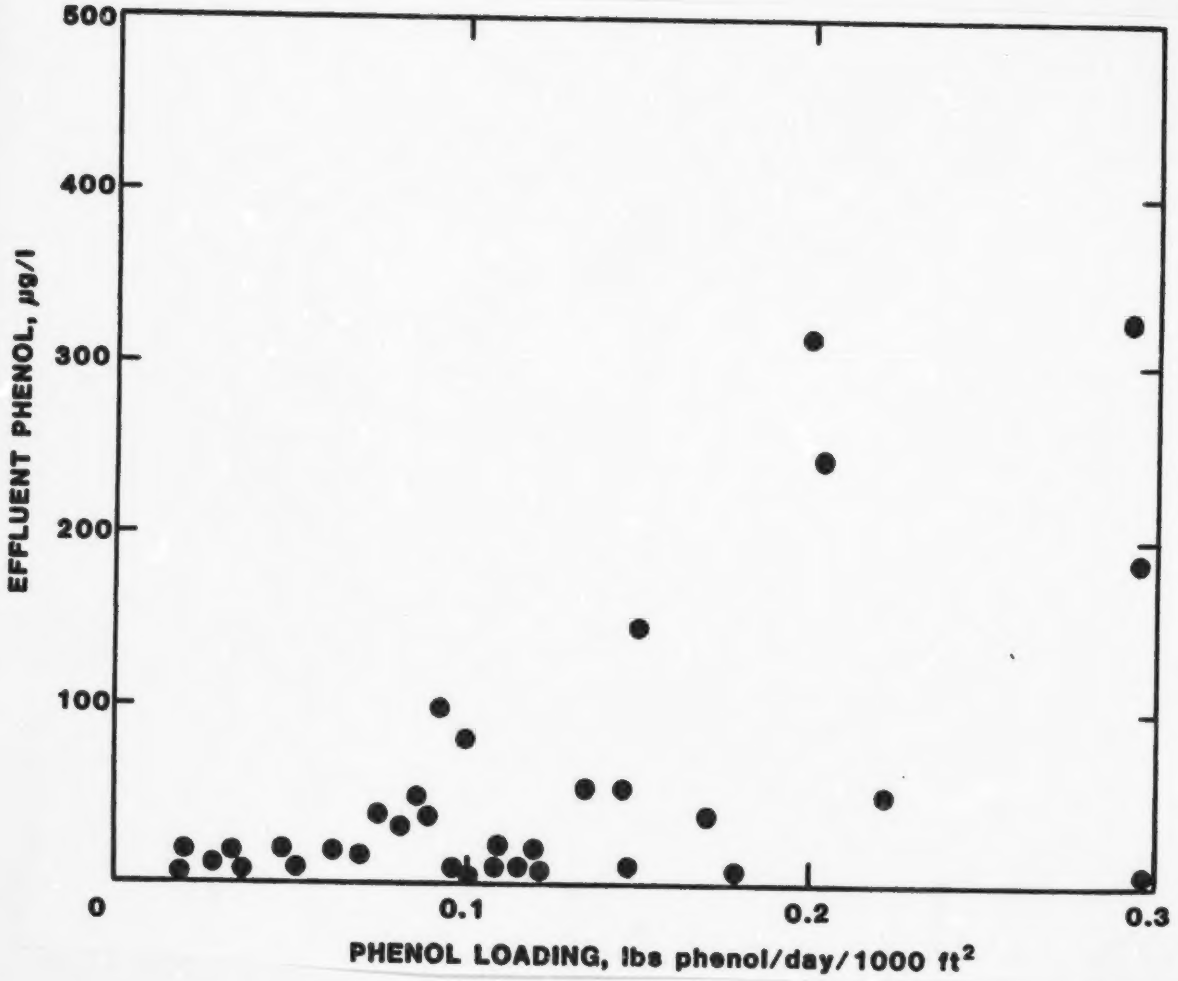


Figure V.8: Effluent Phenol versus Phenol Loading Rate

concentration achieved by an RBC as a function of the phenol loading. It is seen that very low levels of effluent phenol can be achieved by the RBC process.

Kincannon and Stover (1983) have suggested alternative designs for biological treatment of contaminated ground water in which treatability studies were conducted. In this case, the contaminated ground water undergoes metals removal and high temperature air stripping before biological treatment. The quality of the water after metals removal and stripping is shown in Table V.4. Activated sludge and RBC pilot plant studies were conducted and designs suggested for both systems. These designs are shown in Tables V.5 and V.6. The projected effluent qualities from the two systems are shown in Tables V.7 and V.8. It is seen that an excellent effluent is expected. Table V.9 gives the expected priority pollutant levels for various biological treatment processes.

Costs

There are no good data available at this time in regards to the cost of biological treatment of contaminated ground waters. However, the costs should be comparable to those for treating industrial wastewaters.

CHEMICAL PRECIPITATION

Chemical addition for the removal of inorganic compounds is a well-established technology. There are three common basic types of chemical addition systems which depend upon the low solubility of inorganics at a specific pH; (1) the carbonate system, (2) the hydroxide system, and (3)

Table V.4: High Temperature Air Stripper Extract Water Qualities for Biological Studies

Parameter	Well #1	Well #2
pH	6.7	7.2
Specific Conductance, μ MHO_s	450	1300
TOC, mg/l	250	590
COD, mg/l	700	1960
BOD_5, mg/l	450	1025
Total Phenols, mg/l	2.5	4.0
SS, mg/l	25	30
VSS, mg/l	10	16
TDS, mg/l	380	1860
TVDS, mg/l	120	1220
Fe, mg/l	1.7	0.4
Mn, mg/l	0	2.3
NH_3-N, mg/l	5.5	9.0
Ortho-P, mg/l	0.2	0.2

Table V.5: Design Summary for Activated Sludge System

Reactor Volume	60,000 gallons, or two-30,000 gallons each
MLVSS	1500 mg/1
Maximum BOD Removed	600 lbs BOD_5/day
Oxygen Requirements	
Energy Oxygen	0.4 lbs O_2/lb BOD_5 removed
Endogenous Oxygen	6.3 lbs O_2/hr/1,000 lbs MLVSS UA
Total Oxygen	710 lbs O_2/day
Nutrient Requirements	
Nitrogen	30 lbs/day, as N
Phosphorus	6 lbs/day, as P
Alpha (α)	0.61
Beta (β)	0.99
Water Temperature	90°F (32°C)
Elevation	300 ft
Oxygen Transfer Characteristics	
N_o	3.0 lbs O_2/Hp-hr
N	1.9 lbs O_2/Hp-hr
Diffused Air	500 Scfm
Net Sludge Production	0.42 lbs/lb BOD_5 removed 250 lbs/day
Secondary Clarifier	
Overflow Rate	500 gpd/ft^2
Underflow Solids Concentration	10,000 mg/1
Recommended Recycle Pump Capacity	Variable up to 50 gpm
Sludge Dewatering Characteristics	
Vacuum Filter Yield	1.0 to 1.5 lb/hr/ft^2
Cake Dry Solids Content	12 to 18%
High Molecular Weight Cationic Polymer	20-40 lb/ton
Ferric Chloride	70-100 lb/ton

Table V.6: Design Summary for RBC System

Surface Area	300,000 ft^2 Three Standard Density RBC Shafts Two Stages Two Shafts/First Stage
Maximum BOD Removed	600 lbs BOD_5/day
Nutrient Requirements	
Nitrogen	30 lbs/day, as N
Phosphorus	6 lbs/day, as P
Net Sludge Production	0.25 lbs/1b BOD_5 removed 150 lbs/day
Secondary Clarifier	
Overflow Rate	500 gpd/ft^2
Underflow Solids Concentration	10,000 mg/1
Sludge Dewatering Characteristics	Similar to Activated Sludge (Based on CST Comparisons)

Table V.7: Projected Effluent Qualities from Activated Sludge Design

Soluble Effluent Qualities, mg/l	Flow = 25 gpm		Flow = 50 gpm	
	x = 1500[a]	x = 2000	x = 1500	x = 2000
Well #1 Quality V = 30,000 gallons				
BOD_5	10	9	13	11
COD	53	52	57	55
TOC	28	26	33	30
Well #1 Quality V = 60,000 gallons				
BOD_5	8	7	10	9
COD	51	50	53	52
TOC	25	24	28	26
Well #2 Quality V = 30,000 gallons				
BOD_5	12	5	28	19
COD	148	125	231	191
TOC	88	74	137	114
Well #2 Quality V = 60,000 gallons				
BOD_5	1	1	10	5
COD	104	95	145	126
TOC	60	55	85	75

[a] x denotes mixed liquor volatile suspended solids (mg/l)

Table V.8: Projected Effluent Quality from RBC Design

Soluble Effluent Quality	Flow = 25 gpm	Flow = 50 gpm
Well #2 Quality 3 RBC Shafts		
BOD_5	1	2
COD	94	96
TOC	60	65

Table V.9: Results of Specific Compound Studies

Specific Compound	HMAS Extract	A.S. #1 Well #1	A.S. #2 Well #2	A.S. #3 (Well #2	A.L. Water)	RBC
Total Phenols	2500(4000)	80(130)	60(115)	50(100)	50(70)	-(100)
Acid Extractables						
2-Chlorophenol	1080(200)	≤10(≤10)	≤10(≤10)	≤10(≤10)	≤10(≤10)	-(≤10)
Phenol	675(990)	≤10(≤10)	≤10(≤10)	≤10(≤10)	≤10(≤10)	-(≤10)
2, 4,-Dimethylphenol	≤10(5300)	≤10(≤10)	≤10(≤10)	≤10(≤10)	≤10(≤10)	-(≤10)
Pentacholrophenol	ND(510	ND(95)	ND(80)	ND(70)	ND(≤10)	ND(90)
Base Neutral Extractables						
1, 4-Dichlorobenzene	105(85)	≤10(≤10)	≤10(≤10)	≤10(≤10)	≤10(≤10)	-(≤10)
1, 2-Dichlorobenzene	1920(430)	335(425)	335(155)	110(270)	100(≤10)	-(≤10)
Naphthalene	715(55)	70(50)	80(25)	25(≤10)	25(≤10)	-(≤10)
Volatile Organics	N.D.(N.D.)					

All analysis in micrograms/liter
N.D. - None Detected
A.S. #1 - High F/M Activated Sludge
A.S. #2 - Medium F/M Activated Sludge
A.S. #3 - Low F/M Activated Sludge
A.L. - Aerated Lagoon
RBC. - Rotating Biological Contactor

the sulfide system. In reviewing the basic solubility products for these systems, the sulfide system removes the most inorganics, with the exception of arsenic, because of the low solubility of sulfide compounds. This increased removal capability is offset by the difficulty in handling the chemicals and the fact that sulfide sludges are susceptible to oxidation to sulfate when exposed to air, resulting in resolubilization of the metals. The carbonate system is a method which relies on the use of soda ash and pH adjustment between 8.2 and 8.5. The carbonate system, although workable in theory, is difficult to control. The hydroxide system is the most widely used inorganics/metals removal system. The system responds directly to pH adjustment, and usually uses either lime (CaOH) or sodium hydroxide (NaOH) as the chemical to adjust the pH upwards. Sodium hydroxide has the advantage of ease in chemical handling and low volume of sludge. However, the hydroxide sludge is often gelatinous and difficult to dewater.

Description of Process

Chemical precipitation can be accomplished by either batch or continuous flow operations. If the flow is less than 30,000 gpd, a batch treatment system would be the most economical. In the batch system, two tanks are provided, each with a capacity of one day's flow. One tank undergoes treatment while the other tank is being filled.

When the daily flow exceeds 30,000 gpd, batch treatment is usually not feasible because of the large tankage required. Continuous treatment may require a tank for acidification and reduction, then a mixing tank for chemical addition, and a settling tank.

Design Parameters and Procedures

The important design factors that must be determined for a particular water during treatability studies include:

(1) Best chemical addition system

(2) Optimum chemical dose

(3) Optimum pH conditions

(4) Rapid mix requirements

(5) Flocculation requirements

(6) Sludge production

(7) Sludge flocculation, settling, and dewatering characteristics

Laboratory-scale test procedures consisting of jar test studies have been used for years, and the test methodology developed is such that full-scale designs can be developed from these studies with a high degree of confidence. Some general design considerations include:

(1) The retention time in the reduction tank should be at least four times the theoretical time for complete reduction.

(2) Twenty minutes will usually be adequate for flocculation.

(3) Final settling should not be designed for an overflow rate in excess of 500 gal/day/ft^2.

Applications to Ground Water

Chemical precipitation has been successfully used for removing heavy metals from various waters. Kincannon and Stover (1983) reported the results of treating a contaminated ground water by various processes. The results of chemical precipitation to remove metals is given in Table V.10. They found that all the metals found in that particular ground water were removed to acceptable levels.

Table V.10: Removal Chemical Precipitation Data for Metals

Compound	Concentrations in Groundwater, mg/ℓ			
	Raw Water	Lime-Treated Water		
		pH 9.1	pH 9.9	pH 11.3
Arsenic	0.12	0.03	0.03	0.03
Barium	0.24	0.17	0.15	0.19
Cadmium	0.003	<0.001	<0.001	<0.001
Chromium (total)	0.09	0.006	0.006	0.006
Lead	0.03	0.006	0.006	0.006
Mercury	<0.001	<0.001	<0.001	<0.001
Selenium	<0.001	<0.001	<0.001	<0.001
Silver	<0.001	<0.001	<0.001	<0.001
Copper	0.10	<0.001	<0.001	<0.001
Iron	352	0.07	0.07	1.05
Manganese	90	0	0	0
Nickel	1.95	0.05	0.30	0.45
Zinc	0.69	0.36	0.09	0.61

Brantner and Cichon (1981) compared the three precipitation processes. The results of this work is shown in Table V.11. Their work also shows that chemical precipitation is effective in removing metals. However, all methods are not equally as effective. In addition, they found that the carbonate system was the simplest process to operate, the hydroxide process the most reliable, and the sulfide precipitation process was the most complex to operate.

Costs

There is very little information in the literature regarding costs of chemical precipitation. However, Krause and Stover (1982) have presented an excellent cost comparison for removing barium from water supplies. Their cost evaluations for ion exchange, lime softening, and chemical precipitation - direct filtration are shown in Tables V.12 through V.14. All costs are April 1980 dollars. Table V.15 shows a cost comparison of the three processes.

OTHER TREATMENT TECHNIQUES FOR INORGANICS

Chemical precipitation has traditionally been a popular technique for the removal of heavy metals and other inorganics from wastewater streams. However, a wide variety of other techniques also exist. Listed in Table V.16 are some available technologies for the removal of specific inorganic contaminants. The technologies in Table V.16, which also include chemical precipitation, were compiled from Patterson (1978) and represent viable techniques. Patterson (1978) treats each inorganic in more detail by addressing such topics as: sources of the given inorganic; its major industrial uses; proven treatment technologies;

Table V.11: Comparison of Precipitation Treatment Processes

Parameter	Influent (ppm)		Clarifier Effluent (ppm)		Filtered effluent (ppm)	
	Mean	Range	Mean	Range	Mean	Range
	HYDROXIDE PRECIPITATION DATA SUMMARY					
Suspended Solids	42	20-63	22	9-33	9	4-14
pH	7.5	7.0-8.1	9.9	9.7-10.2	9.8	9.5-10.4
Total Cadmium	1.66	0.13-4.30	0.05	0.03-0.10	0.04	0.02-0.06
Total Chromium	1.11	0.07-2.90	1.04	0.07-2.80	0.97	0.06-2.90
Total Copper	0.29	0.12-1.50	0.03	0.02-0.03	0.03	0.02-03
Total Lead	1.7	0.8-2.6	0.2	0.1-0.3	0.2	0.1-0.3
Total Zinc	31	6-91	0.40	0.23-0.75	0.28	0.10-0.66
	CARBONATE PRECIPITATION DATA SUMMARY					
Suspended Solids	43	16-75	27	14-52	6	2-10
pH	7.1	6.7-7.7	8.3	8.1-8.4	8.1	7.8-8.5
Total Cadmium	1.37	0.26-2.90	0.14	0.02-0.27	0.04	0.02-0.06
Total Chromium	0.67	0.23-1.80	0.62	0.17-1.8	0.60	0.14-2.00
Total Copper	0.18	0.06-0.27	0.04	0.03-0.06	<0.03	<0.02-0.04
Total Lead	1.4	0.7-2.1	0.2	0.2-0.4	<0.1	<0.1-0.2
Total Zinc	26	1-67	3.2	0.37-5.0	1.18	0.19-5.00
	SULFIDE PRECIPITATION DATA SUMMARY					
Suspended Solids	90	30-210	37	10-63	5	2-8
pH	6.8	6.4-7.7	8.2	8.0-8.4	8.1	7.8-8.5
Total Cadmium	3.3	0.65-5.4	0.18	0.09-0.29	0.06	0.02-0.12
Total Chromium	0.52	0.02-1.9	0.12	0.08-0.20	<0.05	<0.05-0.05
Total Copper	0.35	0.19-0.96	<0.04	<0.04-0.05	<0.03	<0.02-0.03
Total Lead	4.5	2.3-8.1	0.4	0.2-0.5	<0.1	<0.1-0.2
Total Zinc	93	5.8-220	3.1	2.0-6.2	0.68	0.11-1.8

Data by Brantner and Cichon (1981)

Table V.12: Ion-Exchange System - Cost Estimate Summary

Item	Cost
Capital cost (dollars)	
Aerator	$ 25,000
Wet well	9,500
Transfer pumps	12,700
Ion exchangers	137,500
Caustic soda system	5,600
Brine pit	16,300
Building addition	52,300
Outside piping and sitework	25,900
Electrical and instrumentation	34,200
General and special conditions	22,300
Construction contingencies	51,200
Total construction cost	$392,500
Engineering and estimating contingencies	58,900
Financial cost	13,500
Bond interest	404,600
Total capital cost	$869,500
O & M costs (dollars/year)	
Labor	14,000
Chemicals	23,200
Power	2,400
Waste disposal	1,200
Total annual O & M cost	$40,800

Table V.13: Lime-Softening System-Cost Estimate Summary

Item	Cost
Capital cost (dollars)	
Aerator	$ 25,000
Solids contact reactor	113,600
Gravity filter	222,900
Recarbonation system	51,900
Transfer pumps	12,700
Alum system	10,100
Lime system	40,000
Lime sludge dewatering	93,800
Building addition	209,800
Outside piping and sitework	78,000
Electrical and instrumentation	102,900
General and special conditions	67,200
Construction contingencies	154,200
Total construction cost	$1,182,100
Engineering and estimating contingencies	177,300
Financial cost	40,800
Bond interest	1,218,400
Total capital cost	$2,618,600
O & M cost (dollar/year)	
Labor	28,000
Chemicals	27,500
Power	4,600
Waste disposal	19,100
Total annual O & M cost	$ 79,200

Table V.14: Chemical Precipitation-Direct Filtration System-Cost Estimate Summary

Item	Cost
Capital cost (dollars)	
Aerator	$ 25,000
Rapid mix tank	7,900
Flocculation basin	36,100
Gravity filter	286,600
Recarbonation system	62,200
Transfer pumps	12,700
Potassium hydroxide system	25,600
Gypsum system	22,400
Polymer system	5,000
Building addition	239,000
Outside piping and sitework	70,500
Electrical and instrumentation	93,000
General and special conditions	60,800
Construction contingencies	139,300
Total construction cost	$1,068,100
Engineering and estimating contingencies	160,200
Financial cost	36,800
Bond interest	1,100,900
Total capital cost	$2,366,000
O & M cost (dollars/year)	
Labor	28,000
Chemicals	116,600
Power	4,900
Waste disposal	6,400
Total annual O & M cost	$ 155,900

Table V.15: Monetary Comparison of Alternative Treatment Systems

Item	Alternative Treatment Systems Ion Exchange System	Lime Softening System	Chemical Precipitation-Direct Filtration System
Capital cost (dollars)	$869,500	$2,618,600	$2,366,000
Capital annual equivalent cost (dollars/year)	116,400	350,000	316,800
Annual O & M cost (dollars/year)	40,800	79,200	155,900
Total annual equivalent cost (dollars/year)	$157,200	$ 429,800	$ 472,700

Table V.16: Treatment Alternatives for Inorganics

Inorganic	Treatment Method
Arsenic	Charcoal Filtration Lime Softening Precipitation with lime + iron Precipitation with alum Precipitation with ferric sulfate Precipitation with ferric chloride Precipitation with ferric hydroxide Precipitation with sulfide Ferric Sulfide Filter Bed Iron or Lime Coagulation + settling + dual media filtration + carbon adsorption
Barium	Iron or Lime Coagulation + settling + dual media filtration + carbon adsorption Precipitation as sulfate Precipitation as carbonate Precipitation as hydroxide Ion Exchange
Boron	Evaporation Reverse Osmosis Ion Exchange
Cadmium	Precipitation as hydroxide Precipitation as hydroxide + filtration Precipitation as sulfide Coprecipitation with ferrous hydroxide Reverse Osmosis Freeze Concentration
Chloride	Ion Exchange Electrodialysis Reverse Osmosis Other (holding basins, evaporative ponds, deep well injection)

Table V.16: (continued)

Inorganic	Treatment Method
Chromium (hexavalent)	Ion Exchange Freeze Concentration Activated Carbon Cementation Reduction (Reduce Cr^{+6} to Cr^3 and precipitation of hydroxide) Reduction with sulfur dioxide Reduction with bisulfite Reduction with bisulfite + hydrazine Reduction with metabisulfite Reduction with ferrous sulfate
Chromium (trivalent)	Precipitation (see above) Ion Exchange
Copper	Precipitation with lime Ion Exchange Evaporative Recovery Electrolytic Recovery Cementation Reverse Osmosis
Cyanide	Alkaline Chlorination Electrolysis Ozonation Evaporation
Fluoride	Precipitation by lime addition Precipitation by magnesium addition Precipitation by alum addition Adsorption on hydroxlapatite beds Adsorption on alumina contact beds

Table V.16: (continued)

Inorganic	Treatment Method
Iron	Oxidation-Precipitation by aeration, sand filtration Oxidation-Precipitation by aeration, lime, sand filtration Oxidation-Precipitation by aeration, coke bed filtration, sedimentation, sand filtration Oxidation-Precipitation by lime, aeration, diatomite filtration Oxidation-Precipitation by chlorination, alum-lime-sodium silicate precipitation, sand filtration (deep well disposal)
Lead	Ion Exchange Precipitation by lime + sedimentation Precipitation by caustic + sedimentation Precipitation by ammonium hydroxide Precipitation by dolmite + sedimentation Precipitation by sodium carbonate + filtration Precipitation by sodium phosphate + filtration Precipitation by ferric sulfate + sedimentation Precipitation by ferrous sulfate + sedimentation
Manganese	Aeration Ion Exchange Catalysis Oxidation-Precipitation by chlorine dioxide addition Oxidation-Precipitation by manganese dioxide addition Oxidation-Precipitation by potassium permanganate addition
Mercury	Precipitation by sodium sulfide addition Precipitation by sodium hydrosulfide addition Precipitation by magnesium sulfide addition Precipitation by sulfide addition Ion Exchange Coagulation with alum Coagulation with iron Activated Carbon

Table V.16: (continued)

Inorganic	Treatment Method
	Reduction to Metallic Form by zinc Reduction to Metallic Form by stannous chloride Reduction to Metallic Form by sodium borohydride
Nickel	Precipitation by lime Precipitation by sulfide Precipitation by alum Ion Exchange Reverse Osmosis Evaporative Recovery
Selenium	Coagulation with lime Coagulation with ferric sulfate Coagulation with alum Activate Carbon + Cation Exchange + Anion Exchange
Silver	Precipitation with ferric chloride Ion Exchange Reductive Exchange with zinc or iron Electrolytic Recovery
Total Dissolved Solids	Reverse Osmosis Electrodialysis Distillation Ion Exchange
Zinc	Precipitation by lime addition Precipitation by caustic addition Ion Exchange Evaporation

proposed treatment technologies; removal efficiencies of various technologies; and costs of various treatment technologies.

TREATMENT TRAINS

Due to the complex composition of most ground waters, no one unit operation is capable of removing all of the contaminants present. It may be necessary to combine several unit operations into one treatment process to effectively remove the contaminants required. In order to simplify, and make visible, the selection of the applicable treatment trains, Table V.17 is presented showing a number of unit operations and the waste types for which they are effective. Results presented by Kincannon and Stover (1983) illustrate the levels of treatment achieved by a treatment train, with these results given in Table V.18.

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Brantner, Karl A. and Edward J. Cichon, "Heavy Metals Removal: Comparison of Alternative Precipitation Processes", Industrial Waste-Proceedings of the Thirteenth Mid-Atlantic Conference, 1981.

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Kincannon, D.F., and E.L. Stover, "Biological Treatability of Specific Organic Compounds Found in Chemical Industry Wastewaters", Presented at the 36th Purdue Industrial Waste Conference, West Lafayette, Indiana, 1981a.

Kincannon, D.F. and E.L. Stover, "Fate of Organic Compounds During Biological Treatment", Presented at the 1981 National Conference on Environmental Engineering, ASCE Environmental Engineering Division, Atlanta, Georgia, 1981b.

Table V.17: Summary of Suitability of Treatment Processes

	Volatile Organics	Non-Volatile Organics	Inorganics
Air Stripping	Suitable for most cases	Not Suitable	Not Suitable
Steam Stripping	Effective Concentrated Technique	Not Suitable	Not Suitable
Carbon Adsorption	Inadequate Removal	Effective Removal Technique	Not Suitable
Biological	Effective Removal Technique	Effective Removal Technique	Not Suitable Metals Toxic
pH Adjustment Precipitation	Not Applicable	Not Applicable	Effective Removal Technology
Electrodialysis	Not Applicable	Not Applicable	Inefficient Operation/ Inadequate Removal
Ion Exchange	Not Applicable	Not Applicable	Inappropriate Technology - Difficult Operation

Table V.18: Ground Water Treatment Results From a Selected Treatment Train

		Parameter's Value After Treatment				
				Activated Carbon Adsorption		
Parameter	Raw Water	Metals Treatment	Steam Stripping	6000 mg/ℓ	24,000 mg/ℓ	Biological Treatment
pH-units	6.0	10.0 to 6.5		6.5	6.6	7.3
Specific conductance-μg/ℓ	2800			2450	2450	
TOC-mg/ℓ	4000	3685	1700	1575	1130	34
COD-mg/ℓ	11750		3600	2400	1950	125
BOD_5-mg/ℓ	7025					5.5
Phenols-mg/ℓ	26			0.85	0.12	0.12
SS-mg/ℓ	360					
VSS-mg/ℓ	142					
TDS-mg/ℓ	3050					
TVS-mg/ℓ	1485					
Arsenic-mg/ℓ	0.12	0.03		0.02	0.02	
Barium-mg/ℓ	0.25	0.15		0.09	0.03	
Cadmium-mg/ℓ	0.003	<0.001		<0.001	<0.001	
Chromium-mg/ℓ	0.09	0.006		0.006	0.006	
Lead-mg/ℓ	0.03	0.006		0.006	0.006	
Mercury-mg/ℓ	<0.001	<0.001		<0.001	<0.001	
Selenium - mg/ℓ	<0.001	<0.001		<0.001	<0.001	
Silver-mg/ℓ	0.001	<0.001		<0.001	<0.001	
Copper-mg/ℓ	0.10	<0.001		<0.001	<0.001	
Iron-mg/ℓ	352	0.07		0.07	0.07	
Manganese-mg/ℓ	90	0		0	0	
Nickel-mg/ℓ	1.95	1.58		0.89	0.28	
Zinc-mg/ℓ	0.69	0.09		0.09	0.09	
Tetrahydrofuran- μg/ℓ	22000		*			*
1,1,1-Trichloroethane- μg/ℓ	150000		*			*
Benzene- μg/ℓ	68750		*			1897**

(continued)

Table V.18: (continued)

		Parameter's Value After Treatment				
				Activated Carbon Adsorption		
Parameter	Raw Water	Metals Treatment	Steam Stripping	6000 mg/ℓ	24,000 mg/ℓ	Biological Treatment
Trichloroethylene- μg/ℓ	338000		*			
Methyl isobutyl ketone-μg/ℓ	76400		*			1098
Xylenes- μg/ℓ	*		*			*
Toluene-μg/ℓ	92000		*			25
Ethylbenzene- μg/ℓ	23500		*			*
1,4-Dichlorobenzene- μg/ℓ	35	35	17	*	*	*
1,2-Dichlorobenzene-μg/ℓ	5	5	*	*	*	*
Naphthalene- μg/ℓ	≤1	≤1	≤1	≤1	*	*
2-Chlorophenol-μg/ℓ	540	540	40	≤1	≤1	*
2-Nitrophenol-μg/ℓ	15	*	6	*	*	*
Phenol- μg/ℓ	370	*	20	*	*	*
2,4-Dimethylphenol-μg/ℓ	20	*	*	*	*	*
o-Cresol-μg/ℓ	80	80	25	*	*	*
m-Cresol-μg/ℓ	220	220	*	≤1	*	*
Benzoic acid-μg/ℓ	1230	1230	*	*	*	*
Pentachlorophenol-μg/ℓ	40	40	40	8	2	*

* No peaks on chromatograms

** Benzene and trichloroethylene peaks combined into one peak

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SECTION VI

IN-SITU TECHNOLOGIES

This section addresses aquifer restoration measures involving treatment in-place. Included is brief information on in-situ chemical treatment along with more extensive information on the use of both natural and enhanced microbiological processes. In-situ treatment can be used singly or in combination with other aquifer restoration strategies.

IN-SITU CHEMICAL TREATMENT

In-situ chemical treatment of contaminated ground water can be considered only in cases where contaminants are known, and the levels and extent of contaminated water in the aquifer are defined. In-situ treatment generally involves the installation of a bank of injection wells at the head of, or within the plume of contaminated ground water. A treatment agent is then pumped into the aquifer. The treatment agent must be specific for different classes of contamination. For example, heavy metals may be made insoluble and rendered immobile with alkalies or sulfides, cyanides can be destroyed with oxidizing agents, cations may be precipitated with various anions or by aeration, and hexavalent chromium could be made insoluble with reducing agents.

Description of Process

The process of in-situ treatment can be accomplished by many means. Two examples will be described herein. The first is a process to remove iron and manganese called the Vyredox Method (Hallberg and

Martinelli, 1976). This method was developed in Finland and is now used in several European countries. The aim of the Vyredox Method is to achieve a high degree of oxidation in the strata around a well. In other words, the Eh and pH are kept so high that the iron and manganese are precipitated and retained in the strata. The Vyredox concept is illustrated in Figure VI.1. The water that enters the well is thus free of iron and manganese. Iron is precipitated first in the zone furthest from the withdrawal (supply) well. The number of living bacteria increases as the withdrawal well is approached, and so does the number of dead bacteria. The organic matter contained in the dead cells becomes a carbon source for the bacteria that preferentially oxidize manganese. This process takes place nearer the well, where the Eh is higher. Thus, the Vyredox Method provides favorable conditions for removing iron first, and then manganese.

Figure VI.2 illustrates a Vyredox plant for treating contaminated ground water. It consists of one or more wells for supplying water. Each well has a pipe fitted with a screen. A number of injection wells (aeration wells) are situated in a ring around each supply well. The number depends on the hydrogeological and geochemical conditions. Conduits connect each well to a nearby building. The water forced into the injection wells must first be degassed and enriched with oxygen. This is done in a special aerator, the oxygenator.

A procedure of containment of a contaminant by polymerizing the contaminant in the ground has been reported by Williams (1982). The procedure has been used to contain approximately 4,200 gallons of acrylate monomer which had leaked from a corroded underground pipeline.

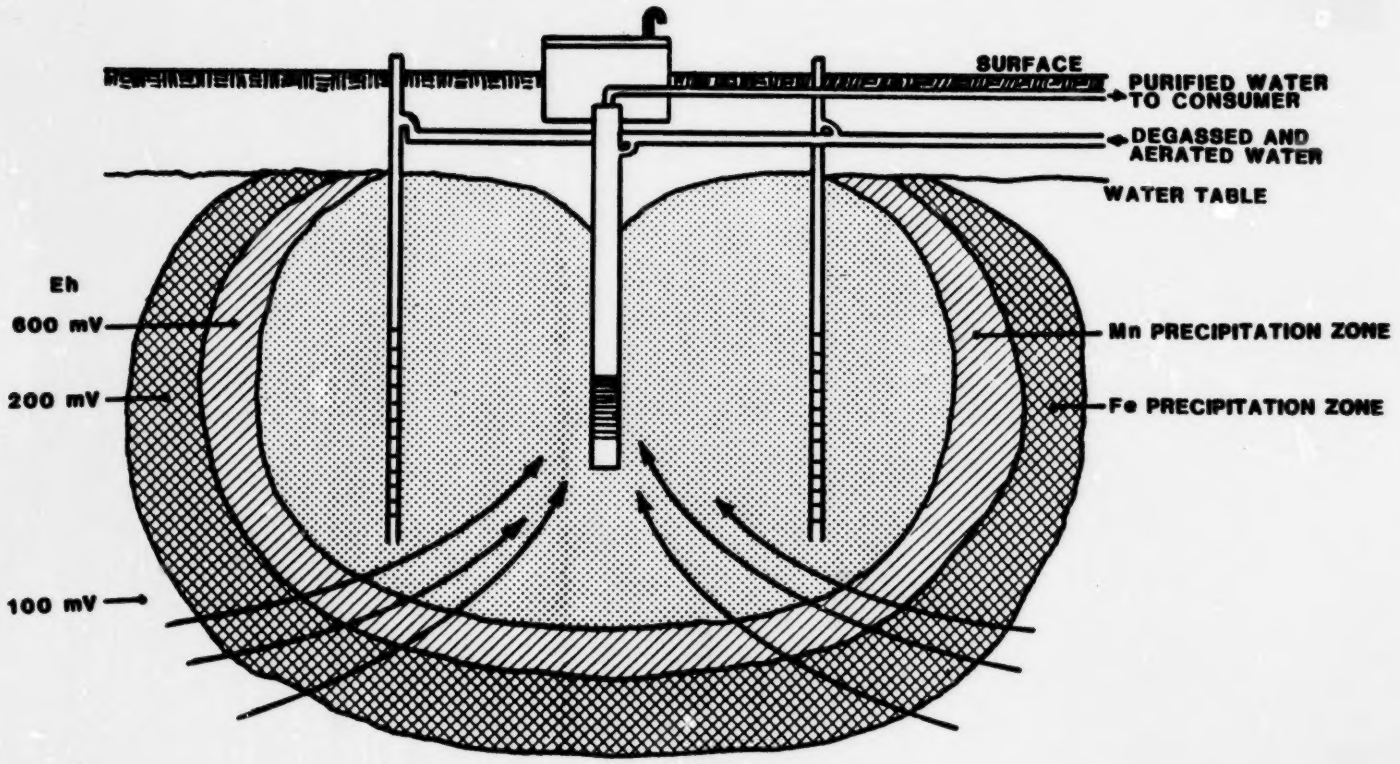
SURFACE
PURIFIED WATER TO CONSUMER
DEGASSED AND AERATED WATER
WATER TABLE
Eh
600 mV
200 mV
100 mV
Mn PRECIPITATION ZONE
Fe PRECIPITATION ZONE

Figure VI.1: Vyredox Concept

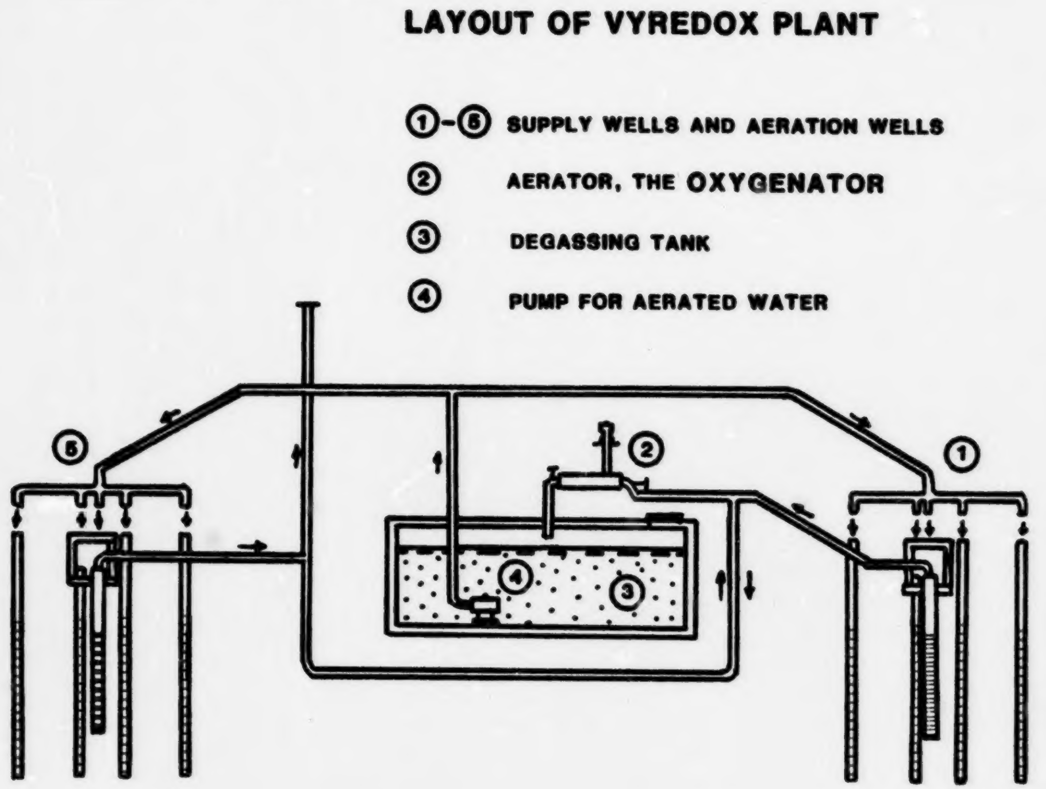
LAYOUT OF VYREDOX PLANT
①-⑤ SUPPLY WELLS AND AERATION WELLS
② AERATOR, THE OXYGENATOR
③ DEGASSING TANK
④ PUMP FOR AERATED WATER
⑤
②
①
④
③

Figure VI.2: Vyredox Plant with Two Supply Wells Complete with Aeration Wells and Oxygenator Building

The acrylate monomer is a colorless mobile liquid less heavy than and only moderately soluble in water. Vapors from the monomer are odorous at 5 ppm, and in high concentrations can result in skin irritation, as well as explosive potential. Under favorable conditions, the monomer will polymerize to a soft rubbery texture.

Because imposed limitations, both by the hydrogeologic conditions and by the practical characteristics of the site, there were few viable options for recovering or containing the monomer. Therefore, a system of four exfiltration galleries was designed and installed. Two-inch diameter perforated PVC casings, in 40-foot lengths, were buried in narrow trenches two feet below ground surface across the shallow contaminated zone. A riser pipe and manifold header connected each gallery to the solution tanks. Four thousand gallons of catalyst and activator solution per treatment were used. Two separate treatments four days apart were used. It is estimated overall, that 85 to 90 percent of the liquid monomer contaminant was effectively converted to a solidified polymer.

Advantages and Disadvantages

In-situ chemical treatment is viable only under particular hydrogeological and geochemical conditions. Other aquifer restoration measures, such as withdrawal and treatment, may be more appropriate for consideration in meeting a given need.

IN-SITU BIOLOGICAL STABILIZATION

Biological treatment can be used to clean up contaminated aquifers. Microbes can degrade most organic compounds; however, many man-made compounds are relatively refractive (Kobayoshi and Rittman, 1982). Compounds which possess amine, methoxy, and sulfonate groups, ether linkages, halogens, branched carbon chains, and substitutions at the meta position of benzene rings are generally persistent. Environmental factors such as dissolved oxygen level, pH, temperature, oxidation-reduction potential, availability of nutrients, salinity, and the concentration of the compounds often control the biodegradation of the compounds. The number and type of organisms present also play an important role.

Microbial activity is likely to exist in most subsurface regions where ground water is important (McNabb and Dunlap, 1975). Bacterial levels typically around 10^6 organisms/g dry soil have been found for several shallow water table aquifers which have been investigated (Wilson, et al., 1983b). The potential for biodegradation of a variety of compounds in the subsurface has been demonstrated. The degradation of petroleum products has been extensively studied. Litchfield and Clark (1973) analyzed ground water samples from aquifers throughout the United States that were contaminated with hydrocarbons, and found hydrocarbon-utilizing bacteria in all the samples at levels up to 10^6 per ml. After a gasoline spill in Southern California, McKee, Laverty and Hertel (1972) found 50,000 gasoline-utilizing bacteria/ml or higher in samples from wells which had traces of free gasoline while a non-contaminated well had only 200 organisms/ml. Jamison, Raymond, and Hudson, Jr. (1975) determined that the microbial population in an aquifer contaminated by a gasoline pipeline break was limited by inadequate levels of nitrogen, phosphorus, and oxygen. Experiments with microbial isolates from the ground water showed that the different isolates were able to utilize certain components of the gasoline and suggested that co-oxidation played an important role in the biodegradation of the other compounds (Jamison, Raymond, and Hudson, Jr., 1976). Complete conversion of hydrocarbons leads to carbon dioxide, water, and new cell biomass; various intermediates are also formed (Vanloocke, et al., 1975). In their column studies, Kappler and Wuhrman (1978a, b) noted a lag period of 1 to 5 days (depending on temperature) before the ground water microbial flora was able to measurably degrade dissolved hydrocarbons. Addition of nitrogen increased degradation. Stimulation of the microbial population by the addition of nitrogen, phosphorus, and dissolved oxygen has been shown to be effective in restoring hydrocarbon-contaminated aquifers (American Petroleum Institute, 1980). Yang and Bye (1979) suggested that the levels of trace elements are usually sufficient to support microbial growth.

Many organic compounds which have contaminated ground water are subject to microbial action. Wilson, et al. (1981, 1983 a and b) studied the degradation of several halogenated volatile organics commonly found as ground water contaminants and determined that some of the compounds were degraded, although often at very slow rates. Differences were noted between the activities of the microbial populations from two sites in degrading the synthetic organics. The degradation of naphthalene has been studied in several systems. Naphthalene has a number of uses and is considered to be hazardous (Windholz, 1976). It should be a representative model for other compounds. Slavnia (1965) and Naumova (1960) found naphthalene-utilizing organisms in the ground waters of the U.S.S.R. near oil and gas beds. Ogawa, Junk, and Svec (1981) and Lee and Ward (1984) reported that naphthalene was degraded rapidly in aerobic ground waters contaminated by polynuclear aromatic hydrocarbons. However, Erlich, et al. (1982) concluded that there was no evidence of anaerobic degradation of naphthalene in ground water samples from an area contaminated by wood creosoting products, although it was disappearing at a faster rate in the aquifer than if only dilution were occurring. Naphthalene was slightly sorbed onto sediments. It was biodegraded in an aquifer recharged with reclaimed water from wastewater treatment after an initial lag (Roberts, et al., 1980). The importance of acclimation to the contaminant was demonstrated by these results.

Many ground water systems are deficient in oxygen and consequently anaerobic degradation is important. Erlich, et al. (1982) and Rees and King (1980) reported evidence of anaerobic degradation of phenolics under aquifer conditions. Bouwer, Rittman, and McCarty (1981) and Bouwer and McCarty (1983a, b) found degradation of several halogenated aliphatic organic compounds under methanogenic and denitrifying anaerobic conditions that were not degraded under aerobic conditions. Wood, et al. (1980) reported that anaerobic metabolism of some of these compounds led to the formation of similar contaminants such as the production of vinyl chloride, vinylidene chloride, cis and trans 1,2-dichloroethene from trichloroethylene and/or tetrachloroethylene. None of the aromatic compounds tested by Bouwer and McCarty (1983b) were significantly utilized under anaerobic conditions. DiTommaso and Elkan

(1973) and Leenheer, Malcolm, and White (1976) disclosed that methane was produced by the degradation of a high organic content wastewater after deep well injection. This provides evidence for anaerobic degradation in the deep subsurface.

The potential for microbial degradation of contaminants has been utilized to restore polluted environments. Atlas (1977) outlined the following approaches that can be used to enhance the degradation of petroleum: the microbial population can be altered by seeding; the environment can be modified to enhance microbial activity; or the petroleum can be modified to make it more susceptible to biodegradation. Seed microorganisms would probably have to be a mixture of microorganisms that collectively can degrade all the components of the contaminant. Different mixtures of seed organisms will have to be used for different environments and contaminant problems. The environment can be modified to enhance microbial activity by the addition of dissolved oxygen, nitrogen, phosphorus, sulfur, iron, magnesium, calcium, sodium, and water which are not present in sufficient quantities. Modification of the contaminant could involve increasing the surface area available for biodegradation by dispersing the contaminant or by emulsification. However, the emulsifying agent or dispersant may prove toxic to the microbial population (Atlas, 1977).

Biological restoration of contaminated aquifers has been accomplished using several techniques. Suntech pioneered the use of "Bioreclamation" to restore petroleum contaminated aquifers (Raymond, 1974, 1978; Raymond, Hudson, and Jamison, 1976; and Jamison, Raymond and Hudson, 1975). This process enhances the natural population by providing dissolved oxygen and nutrients to accelerate biodegradation. This process has been modified for use at hazardous waste sites (J.R.B. Associates, 1982; and Jhaveri and Mazzacca, 1982). Another technique which has been employed is the addition of acclimated microbes and nutrients to stimulate degradation (Quince and Gardner, 1982). Yet another option is withdrawal and biological treatment by conventional wastewater treatment processes, including activated sludge, lagoons (facultative, anaerobic, or aerobic), rotating biological disks, and trickling filters (J.R.B. Associates, 1982). Combinations of these biological techniques with physical-chemical treatment have also been used effectively (Shuckrow and Pajak, 1981).

Enhancement of the Indigenous Population

Stimulation of the native microbial population by the addition of nutrients has long been suggested as a means of increasing the degradation of hydrocarbons in aquatic and soil environments. In marine environments, hydrocarbon degraders have been found in higher concentrations in regions chronically polluted with petroleum (Atlas, 1977). Nitrogen and phosphorus levels are often inadequate and must be supplemented. Use of an oleophilic fertilizer that concentrates the nutrients at the water surface has been shown to increase the degradation of oil slicks (Atlas and Bartha, 1973b). Levels of iron may also be deficient (Dibble and Bartha, 1976). The temperature of the sea water is a controlling factor in microbial degradation (Mulkin-Phillips and Stewart, 1974b), especially in colder areas like the Arctic (Atlas and Schofield, 1975). Seasonal and climatic variability, the types of hydrocarbons involved, and the nature of the site are also important (Colwell and Walker, 1977). Other factors to be considered include the dispersion of the hydrocarbon, turbulence, the concentration of the hydrocarbon, and microbial predation (Zobell, 1973). The effectiveness of nutrient supplementation has also been demonstrated in freshwater systems; nutrient addition increased the degradation of gasoline in a lake from 90 (control) to 96 percent (nutrient supplemented) after five weeks (Horowitz and Atlas, 1977).

Addition of nutrients to hydrocarbon-contaminated surface soil has proven useful in increasing microbial degradation. The total numbers of microbes increase greatly after a petroleum spill; Odu (1972) noted an increase from 10^6 organisms/g to 10^8 organisms/g after an oil well blowout. Application of fertilizer stimulated greater microbial growth and utilization of some components of oil (Jobson, et al., 1974). Other components of oil are not attacked by the microbes and remain in the soil. Saturated fractions are highly degraded while asphaltenes and aromatics are often resistant to microbial attack (Jobson, Cook, and Westlake, 1972). Lehtomaki and Niemela (1975) found that the addition of yeast cells also served as a nutrient source. The soil must be tilled to distribute the hydrocarbons through the soil and provide oxygen (Raymond, Hudson, and Jamison, 1976). Wenstel, et al. (1981) attempted to enhance the biodegradation of monochlorobenzene and Ethion by the addition of nutrients (Difco nutrient broth) and aeration of the soil. No evidence for significant microbial degradation of monochlorobenzene or Ethion was observed, thus showing that stimulation of the native microbial population will be ineffective against compounds which the microbes cannot readily attack, such as the water insoluble Ethion or highly volatile monochlorobenzene.

Enhancement of the natural microflora has been used in a number of cases to degrade hydrocarbons in surface soils. Dibble and Bartha (1979c) documented the cleanup of a large kerosene spill (1.9 million liters) in New Jersey. Much of the kerosene was recovered by physical means and by removing 200 m^3 of contaminated soil. Following stimulation of microbial degradation by liming, fertilization, and tillage, phytotoxicity was reduced. Microbial degradation was slowed by the lower winter temperatures. Guidin and Syratt (1975) suggested that a black covering be placed over the soil to increase the soil temperature during the winter to overcome this problem. Landfarming has been tested as a method of disposing of waste oil and oil sludges. Landfarming relies on the soil organisms to degrade the waste applied to the soil. Brown, et al. (1981) investigated the factors which influenced biodegradation rates of oil sludges at a land farm site. Only under excessively wet or dry conditions did the moisture content become a dominant factor. The nitrogen level was critical since no additional increase in the biodegradation rate occurred when potassium and phosphorus were also added. The optimal carbon to nitrogen ratio ranged from 150:1 to 10:1 depending upon the nature of the sludge. Dibble and Bartha (1979a) conducted similar experiments on landfarming waste oil and determined that carbon to nitrogen and carbon to phosphorus ratios of 60:1 and 800:1 were optimal under the conditions they used. Addition of micronutrients and organic supplements in the form of yeast extract and trace elements or domestic sewage did not prove beneficial. Other experiments showed that urea formaldehyde was the most satisfactory nitrogen source tested since it effectively stimulated biodegradation and did not leach nitrogen which could contaminate the ground water (Dibble and Bartha, 1979b). Weldon (1979) found no adverse impact on ground water quality from landfarming refinery oil sludges, although heavy metals were concentrated in the soil and could be leached away. Another problem was runoff water from the site could contain high amounts of oil and fertilizer (Kincannon, 1972).

These examples illustrate the effectiveness of nutrient supplementation in aquatic and soil systems. Many of the same procedures can be used to restore contaminated aquifers. Among the first to suggest such actions were Williams and Wilder (1971) and McKee, Laverty, and Hertel (1972) who investigated a large gasoline spill (estimated to be 250,000 gallons) in Glendale, California, that had contaminated an irrigation well. An investigation into the microbial degradation of the gasoline showed that several bacterial species of the genera *Pseudomonas* and *Arthrobacter* could utilize the gasoline when supplied with trace nutrients and adequate dissolved oxygen (McKee, Laverty, and Hertel, 1972). Bacterial degradation of trapped gasoline was more rapid in the zone of aeration above the water table than in the water-saturated zone. The levels of gasoline-utilizing bacteria in contaminated wells were 50,000/ml or higher and gradually fell to the background level of 200/ml as the gasoline disappeared. The authors thought that biodegradation could eventually restore the aquifer to service. At roughly the same time, Davis, et al. (1972) recommended that the addition of nutrients to stimulate degradation of hydrocarbons in ground water might be a feasible solution to ground water pollution problems.

Raymond, Jamison and their coworkers at Suntech were probably the first to put these suggestions into operation. Raymond (1974) received a patent entitled "Reclamation of Hydrocarbon Contaminated Ground Waters" on a process to eliminate hydrocarbon contaminants in aquifers by providing nutrients and oxygen to the hydrocarbon-utilizing microorganisms present in the ground water. The nutrients and oxygen are to be introduced through wells and circulated through the contaminated zone by pumping one or more producing wells. Supplementation of the nutrient and oxygen levels and recirculation of the water would allow the normal microbial flora to decompose the hydrocarbons more rapidly than under natural conditions. The nutrient solution would contain sources of nitrogen and phosphorus and other inorganic salts, if necessary, at concentrations of 0.005 to 0.02 percent by weight for each of the nutrients. Oxygen would be supplied by sparging air into the ground water. The process was expected to be largely complete within six months. Return to the normal levels of bacteria would occur after nutrient addition was stopped, and since no organisms were added, the normal flora would be maintained.

Suntech's process has been largely used to clean up gasoline contaminated aquifers. The following steps are involved. Physical methods are employed to recover as much of the gasoline as possible (Suntech, 1977). If practical, it may be wise to continue to pump contaminated wells to contain the gasoline (Raymond, Jamison, and

Hudson, 1976). Then investigations of the hydrogeology and the extent of contamination should be made (Suntech, 1977). A laboratory study must then be conducted to determine if the native microbial population can degrade the components of the spill and what kinds and amounts of inorganic salts are required to stimulate degradation (Raymond, 1978). The laboratory study determines what combination of nutrients gives the maximal cell growth on gasoline in 96 hr at the ambient temperature of the ground water. Considerable variation in the nutrient requirements has been found between aquifers. One system required only the addition of nitrogen and phosphorus sources (Raymond, Jamison, and Hudson, 1976), while the growth of microbes in another aquifer was stimulated best by the addition of ammonium sulfate, mono- and disodium phosphate, magnesium sulfate, sodium carbonate, calcium chloride, manganese sulfate, and ferrous sulfate (Raymond, et al., 1978). The form of the nutrient which must be added also varies; ammonium sulfate gave much greater growth than ammonium nitrate in one aquifer system. Chemical analyses of the ground water provides little information as to the nutrient requirements for the system. After the microbial investigation has established the optimal growth conditions, the system for injecting the nutrients and oxygen and producing water to circulate them in the formation must be designed and built (Raymond, 1978). This work should be under the direction of a competent ground water geologist since controlling the ground water flow is critical to the success of the operation. Placement of the injection and production wells such that ground water flow goes through the contaminated zone is required. Recycling the contaminated water from the producing wells is suggested, since it eliminates the problem of waste disposal and allows the recirculation of unused nutrients. The screens for the wells should be large enough to permit fluctuations of the ground water table due to weather conditions or operation of the system.

Once actual operations are underway, nutrient addition can be by batch or continuous feed (Raymond, 1978). Batch addition gives satisfactory results and is more economical. For one system, the nutrients were prepared as a 30 percent concentrate in a tank truck and injected into the aquifer (Raymond, Jamison, and Hudson, 1976). This may have resulted in osmotic shock to the microorganisms which come into contact with the concentrate before dilution. Large amounts of nutrients may be required; at one site, 16.65 tons of chemicals were added (Minugh, et al., 1983), while a total of 87 tons of food grade quality chemicals were purchased to clean up another site (Raymond, Jamison, and Hudson, 1976). Oxygen can be supplied to the aquifer by sparging air into wells with Carborundum diffusers powered by paint sprayer-type compressors (Raymond, Jamison, and Hudson, 1976) or by diffusers made from a short piece of DuPont Viaflo^R tubing for smaller wells (Raymond, et al., 1978). The larger diffusers can provide up to 10 cubic feet of air per minute (SCFM) while the smaller tubing diffusers can provide only 1 SCFM. Another approach was the use of diffusers spaced along air lines buried in the injection trench (Minugh, et al., 1983). The size of the compressor and the number of diffusers is determined by the extent of contamination and the period allowed for treatment (Raymond, 1978). The supply of dissolved oxygen may be the limiting factor in the biostimulation process, especially in low permeability aquifers (Raymond, et al., 1978). As the levels of contamination decrease, the biochemical oxygen demand lessens and the DO level in the water rises. The system must be monitored to insure that the levels of nutrients are at their optimal concentrations and are being evenly distributed, and that the discharge water meets state or Federal requirements (Raymond, 1978). Adequate supplies of nitrogen and phosphate can be readily maintained once breakthrough has occurred (Raymond, et al., 1978).

The bacterial population's response to nutrient addition should also be monitored. The highest microbial population is likely to be in the area of greatest contamination (up to 10^7 organisms/ml have been reported); a map of the bacterial counts following a gasoline spill in Ambler, Pennsylvania, resembled the contours of gasoline contamination (Raymond, Jamison, and Hudson, 1975). During the course of the biostimulation program at this site, 32 cultures thought to be the predominant gasoline-utilizing bacteria were isolated from the ground water. These cultures included 10 cultures assigned to Nocardia, two Micrococcus, four cultures of Actinetobacter, eight Pseudomonas, Flavobacterium devorars, and seven unidentified cultures. Nocardia cultures were probably responsible for the major paraffinic hydrocarbon degradation, and the Pseudomonas cultures were responsible for much of the aromatic degradation (Jamison, Raymond, and Hudson, 1976). Co-oxidation seemed to have played a major role in the degradation since none of the isolates could grow on branched paraffins, olefins, or cyclic alkanes as sole carbon sources. Bacteria capable of degrading these compounds may also not have been isolated. Similar results from the microbiological studies were found during the biostimulation program at Millville, New Jersey (Raymond, et al., 1978). The preliminary tests before the bioreclamation operation began showed the presence of from 10^2 to 10^5 gasoline-utilizing organisms/ml in the ground water. The microbial population responded to the addition of nutrients and oxygen with a ten to thousand-fold increase in the numbers of gasoline-utilizing and total bacteria in the vicinity of the spill, with levels of hydrocarbon-utilizers in excess of 10^6/ml in several wells. The microbial response was an order of magnitude greater in the sand than the ground water. Forty-one cultures were isolated from the soil and ground water at this site, with 17 considered to be *Pseudomonas*, four *Flavobacterium*, eleven *Nocardia*, and nine were not assigned to any genus. Several of the *Pseudomonas* species were fluorescent in contrast to the Ambler bacteria which did not include fluorescent pseudomonads. Many of the cultures were composed of very small cells. After biostimulation at a LaGrange, Oregon site, bacterial levels increased up to six million times the initial levels.

Suntech's bioreclamation process has met with reasonable success when applied to gasoline spills in the subsurface. After the biostimulation program ended at Ambler, Pennsylvania, the gasoline-utilizing bacterial levels declined from the high levels present during the period of nutrient addition. This suggested a depletion of nutrients and gasoline (Raymond, Jamison, and Hudson, 1975). The concentration of gasoline in the produced water was not reduced during the period of nutrient addition, but no gasoline was found in the produced water 10 months after nutrient addition ceased. Estimates based on the amount of nitrogen and phosphate retained in the system suggested that 744 to 944 barrels of gasoline were degraded. Residual gasoline was found at the last sampling period at the Millville, New Jersey, site, but no free hydrocarbon was observed in any of the wells after the biostimulation program (Raymond, et al., 1978). The gasoline concentrations in cores taken from the aquifer did not seem to change substantially. Initially, the level of phenol in the ground water was a problem, but it decreased to acceptable values after more aerobic conditions were achieved in the aquifer. In the produced water which had been circulated through the site, gasoline levels remained low and fairly constant. The operation was successful in cleaning up the aquifer to the point where no free gasoline was present and the site met state approval. The operation was terminated and all well casings and injection equipment removed. The nutrient supplementation program succeeded in removing all the free product in the wells at the La Grange, Oregon site (Minugh, et al., 1983); however, gasoline odors and a cloudy sheen were detected in some of the pits dug after the cleanup operation ended. Gasoline concentrations of 100 to 500 ppm were found in the areas where the pits were dug with the average level of dissolved organic carbon in the ground water at 20 ppm. Samples taken later showed continued improvement. Vapor problems which had threatened two restaurants were mitigated.

The advantages of the biostimulation process include:

(1) Useful for the removal of hydrocarbons and certain organic compounds, especially water soluble pollutants and low levels of other compounds which would be difficult to remove by any other means.

(2) Environmentally sound since no waste products are generated and no ecological changes result because it utilizes the indigenous microbial flora.

(3) Fast, safe, and generally economical.

(4) Treatment moves with the plume.

(5) Good for short term treatment of contaminated ground water (Yang and Bye, 1979; J.R.B. Associates, 1982).

Its disadvantages are:

(1) Does not work with heavy metals and some organics.

(2) Bacteria can plug the soil and reduce circulation.

(3) Introduction of nutrients could adversely affect nearby surface water.

(4) Residues may cause taste and odor problems.

(5) Could be expensive since equipment maintenance may be high and long term injection of oxygen and nutrients may be necessary to sustain high rates of degradation.

(6) Under certain conditions, such as high concentrations of pollutants, it may be slower than physical recovery methods.

(7) Long term effects are unknown.

The bioreclamation process has been demonstrated to be useful in the cleanup of hydrocarbon-contaminated aquifers of varying properties. Concern was once expressed that the process might not be effective in aquifers with low permeabilities. A laboratory study showed that gasoline-utilizing bacteria could penetrate sand columns with effective permeabilities ranging from 200 darcys to 3.5 darcys (sand packs of coarse 20 mesh sand to very fine 80+ mesh sand) and consolidated sandstone cores with effective permeabilities of 19 and 75 millidarcys (Raymond, Jamison, and Hudson, 1975). The process has been used to restore aquifers of dolomite (Raymond, Jamison, and Hudson, 1976), a highly permeable sand (Raymond, et al., 1978), and alluvial fan deposits composed of sand, gravel, cobbles, and some clay and silt (Minugh, et al., 1983).

Alternative sources of oxygen have been suggested as a means to increase the degradative activity in contaminated aquifers (Texas Research Institute, 1982a). For example, hydrogen peroxide could be injected into the contaminated soil above the water table in conjunction with nutrients where it would decompose naturally or by enzymatic action to increase the dissolved oxygen content. Hydrogen peroxide is relatively inexpensive and does not present a persistent hazard in ground waters (Texas Research Institute, 1982b). It is cytotoxic, but many bacterial cells have enzymatic defenses (hydroperoxidases) against it. Hydrogen peroxide was shown to be toxic to fresh bacterial cultures at levels greater than 100 ppm, although mature cultures suffered less and could function at levels as high as 10,000 ppm (Texas Research Institute, 1982a). Another concern was that the hydrogen peroxide would decompose before it reached the ground water; however, phosphate buffered solutions at a pH of 7.0 and moderate flow rates were effective for maintaining hydrogen peroxide levels (Texas Research Institute, 1982c). Subsequent experimentation with sand columns inoculated with gasoline and gasoline-degrading bacteria showed that 1.0, 0.5, and 0.25 percent hydrogen peroxide solutions were toxic to the bacteria (Texas Research Institute, 1983). Nagel, et al. (1982) documented the use of ozone to treat petroleum contamination in Karlsruhe, Germany, that threatened a drinking water supply. The polluted ground water was withdrawn, treated with ozone, and infiltrated back into the system, via three infiltration wells. About 1 g of ozone per g of dissolved organic carbon (DOC) was added to the ground water which increased the biodegradability of the petroleum contaminants and added dissolved oxygen; the dissolved oxygen levels increased in the ground water and reached equilibrium at about 80 percent of the initial concentration injected. The oxygen consumption peaked at about 40 kg/day during the initial infiltration period. The DOC values in the wells fell from a range of 2.5 to 5.5 g/m^3 to a steady state of about 1.5 g/m^3. Levels of cyanide, a contaminant identified after the treatment began, also decreased although biodegradation was not shown to be the cause. Total bacterial counts in the ground water increased tenfold, but potentially harmful bacteria did not increase. The drinking water from this aquifer contained no trace of contaminants after 1½ years of ozone treatment.

Jhaveria and Mazzacca (1982) of Groundwater Decontamination Systems (GDS) adapted the biostimulation process to the cleanup of an aquifer contaminated with compounds other than petroleum hydrocarbons; the pollutants were solvents including methylene chloride, acetone, n-butyl alcohol, and dimethylaniline. The contamination problem resulted from a spill from a pharmaceutical company, Biocraft Laboratories, in Waldwick, New Jersey where nearly 136,500 kg of the solvents were estimated to have been lost. After consultation with Geraghty and Miller, Inc., the initial consulting firm in Princeton-Aqua Science, and Suntech, Inc., it was decided to contain the contaminated ground water on site and treat it by stimulating the natural microbial population. The contaminated ground water was pumped from dewatering trenches and wells to two activating tanks where nutrients and oxygen were supplied. The water was then pumped into two settling tanks and later injected into the subsurface enriched with nutrients, oxygen, and microorganisms. A bacterial culture acclimated to the contaminants was established before the biostimulation process began.

The biodegradation process was studied before the system was designed (Jhaveria and Mazzacca, 1982). The wells had a population of 10^3 to 10^4 colonies per ml prior to the biostimulation programs, and the addition of nitrogen and phosphate increased the growth of the organisms as high as four times the control. A pilot study where nutrients and oxygen were supplied to the aquifer showed that the microbial population increased from 10^3/ml to 10^6/ml after seven days and remained constant at that level. A batch process study using a fermentor demonstrated that after an acclimation period of eight days, a rapid decrease in the COD of the ground water was noted; essentially all the compounds were degraded. Additional air gave a quicker response. Two continuous process studies were initiated to test the design of the plant. They demonstrated that the addition of oxygen and nutrients to the acclimated bacteria led to rapid removal rates of from 60 to 90 percent of the methylene chloride, acetone, dimethylaniline, and butyl alcohol.

These successful tests led to the design and construction of the system (Jhaveria and Mazzacca, 1982). The above-ground portion consisted of two activating tanks and two settling tanks. The activating tanks were maintained at 20°C and supplied with air and the following nutrients: ammonium chloride, monopotassium phosphate, dipotassium phosphate, magnesium sulfate, sodium carbonate, calcium chloride, manganese sulfate, and iron sulfate. The levels of the nutrients were adjusted to provide the necessary nitrogen and phosphorus to stimulate in-situ degradation. Good results were achieved by the system; removal of organics exceeded 95.9% in the above-ground systems, and the levels of contamination in one of the producing wells fell from 91 ppm of methylene chloride and 54 ppm of acetone, to less than 1 ppm after a year. Similar degradation efficiencies were noted for the monitoring wells. Sludge production was minimal since some of the sludge was recycled from the settling tanks to the activating tanks and some was allowed to pass to the recharge trenches to inoculate the soil with acclimated microorganisms. An independent study by Professor W.W. Umbreit of Rutgers University confirmed that methylene chloride was oxidized by the GDS culture.

Enhancement of the microbial population has also been reportedly used to reduce levels of iron and manganese in the ground water (Hallberg and Martinelli, 1976). The process known as the Vyrodex method was developed in Finland and has been used in Sweden and other locales where high levels of iron and manganese are found in the ground water. Iron bacteria and manganese bacteria oxidize the soluble forms of iron and manganese to insoluble forms; the bacteria use the electrons adsorbed from the oxidation process as sources of energy. The Vyrodex method works by adding dissolved oxygen to the ground water to stimulate the iron and manganese to first remove the iron and later the manganese. As the iron bacteria population builds up and begins to die, it supplies the organic carbon necessary for the manganese bacteria. The efficiency of the process increases with the number of aerations. Since no data was presented that shows an increase in the number of iron and manganese bacteria or in their activity, it is difficult to attribute the reduced level of iron and manganese in the ground water to microbial activity instead of chemical oxidation from the introduction of dissolved oxygen.

Microbial activity in contaminated aquifers can also be enhanced by altering the contaminant chemically or physically to make it more degradable. One way to do that is to spread the contaminant over a larger area by adding dispersants. Several dispersants were tested on marine samples to determine their effects on the degradation of oil (Atlas and Bartha, 1973a). They were found to increase the rate of mineralization provided the sea water was amended with nitrate and phosphate, but were not able to increase the extent of degradation. Mulkin-Phillips and Stewart (1974a) tested four dispersants and found that only one stimulated biodegradation. The four dispersants supported microbial growth and were not toxic to the microbes, but did cause population changes. Two oil herders tested by Atlas and Bartha (1973a) were determined to increase the mineralization rate, but not the extent of degradation. Application of surfactants has also been advocated to clean-up contaminated aquifers, but they may be toxic and nonbiodegradable (Texas Research Institute, 1979).

Addition of Acclimated Microorganisms

Another approach for restoring contaminated aquifers is the addition of microbes to degrade the pollutants. Usually microbes that have been acclimated to degrade the contaminants are used as "seed"; the microorganisms may have been selected by enrichment culturing or genetic manipulation. A mixed microbial population is often necessary to degrade all the contaminants (Zajic and Daugulis, 1975). Microorganisms can become acclimated to the degradation of compounds by repeated exposure to that substance. Felsot, Maddox and Bruce (1981) reported that bacteria exposed to carbofuran yearly became so active in degrading it, that it was no longer effective against the western corn rootworm. Spain and Van Veld (1983) went so far as to suggest that the microbial community near a pollutant spill might be primed with small amounts of the pollutant to ensure a rapid microbial response. Seed organisms can be isolated by enrichment culturing; the type of microorganisms which are isolated are dependent on the source of the inoculum, the conditions used for the enrichment, and the substrate (Atlas, 1977). Sequential enrichment is a modification of enrichment culturing that allows microorganisms that can more fully degrade the substrate to be isolated. The substrate is inoculated with a microbial population and the organisms which can degrade it are isolated. The undegraded substrate is then used to isolate another set of organisms which are capable of degrading the residual components. This process is continued until none of the substrate remains or no new isolates are made. A potential problem with such enrichments is that the organisms may interfere with each other.

A new approach has recently been developed to induce acclimation by genetically manipulating the microbes. Zitrides (1978) and McDowell, Bourgeouis, and Zitrides (1980) used radiation to increase the genetic variability of an adapted microbial population in hopes of producing strains that could better degrade the contaminant. Selected strains of bacteria chosen for their known ability to degrade similar compounds are exposed to successively increasing concentrations of substrate. The fastest growing strains are irradiated. The genetic alterations should increase the growth rate and fix the desired biochemical capability. The adapted mutant will probably be at a disadvantage in the competition with the native microbial population, and may only be able to proliferate on the substrate upon which it was isolated.

Genetic engineering can be used to increase the degradation capacity of microbes by improving the stability of the organisms, enhancing their activity, providing them with multiple degradative activities, and ensuring that they are safe both to the environment and human health (Pierce, 1982). The ability to degrade some hydrocarbons can be encoded on bits of extrachromosomal DNA known as plasmids. Plasmids can be transferred to an organism to increase the number of compounds which can be attacked. The plasmids can also be fused together to provide multiple degradative traits or to produce a novel or previously unexpressed degradative pathway. Stable strains can be engineered that will not pass on their plasmids or will be capable of growth only under restricted conditions; this should limit their potential for escape into the environment. Environmental conditions such as temperature, pH, substrate concentration, oxygen tension, and competition with the native microbial population may prevent the genetically-engineered organism from reaching its degradative potential.

One successful application of genetic engineering is the development of a bacterial strain capable of degrading 2,4,5-trichlorophenoxyacetic acid (2,4,5-T). This strain was developed using the technique of plasmid-assisted molecular breeding. This herbicide is normally degraded very slowly and only by co-oxidative metabolism

(Kilbane, et al., 1982). Kellogg, Chatterjee, and Chakrabarty (1981) isolated an organism that could degrade 2,4,5-T as its sole carbon source from a chemostat inoculated with microorganisms from a variety of hazardous waste dumping sites and microorganisms harboring a variety of plasmids controlling the degradation of several hydrocarbons. The chemostat was fed with low concentrations of 2,4,5-T and higher concentrations of the plasmid substrates for 8 to 10 months. A 2,4,5-T degrading population was isolated which could degrade up to 70 percent of the 2,4,5-T supplied at 1.5 mg/ml. The strain was identified as *Pseudomonas cepacia* AC1100 (Chatterjee, Kilbane, and Chakrabarty, 1982). The ability of *P. cepacia* AC1100 to degrade 2,4,5-T in soil was tested and it was shown to be able to degrade more than 95 percent of 1 mg/g of 2,4,5-T within a week. Soil samples contaminated with from 1000-20,000 μg/g were inoculated with $5x10^7$ AC1100 cells per g. Complete degradation occurred in samples with 5000 μg/g, and more than 90 percent of the 2,4,5-T was degraded after six weekly applications of AC1100 for the 10,000 μg/g samples (Kilbane, Chatterjee, and Chakrabarty, 1983). Other experiments were conducted to determine the survival of AC1100 in the soil. When added to soil without 2,4,5-T the levels of AC1100 dropped to negligible values after 12 weeks, but following addition of 2,4,5-T the population increased until the compound was exhausted. No appreciable effects on the number or types of indigenous bacteria were noted when 10^7 AC1100 cells were added. This indicates that no adverse ecological effects will occur when AC1100 is used as a seed to remove 2,4,5-T from soil. Until results from field tests are available, it will be difficult to determine how well the organism will work under actual conditions.

There are problems with the use of genetically-engineered microorganisms to degrade contaminants. Johnston and Robinson (1982) could find no conclusive evidence that commercially available genetically-engineered organisms were effective in establishing themselves or significantly enhancing biodegradation of pollutants in aeration basins or natural environments having an active native microbial population. Most of the bacteria typically used in microbial genetic work are eutrophs of the families Enterbacteriaceae and Pseudomonodoceae which may not be able to attack substrates in the parts-per-billion range that are often found in environmental samples. Environmental stress such as unsuitable water quantities or the presence of toxicants may also affect an introduced microorganism. However genetic engineering holds great promise, especially in treatment facilities where conditions can be controlled. These facilities will probably be the first area where gene manipulation will be used.

Seeding microorganisms has been used in a number of different environments to degrade organics. Gutnick and Rosenberg (1977) argued that microbial seeding was ineffective in reducing oil contamination in the sea, but that microbial seeding and nutrient supplementation would work in contained environments like oil tankers. Miget (1972) found that the effectiveness of microbial seeding in simulated marine environments varied with the type and quantity of crude oil more than with the inoculum density or nutrient salts concentration. Several petroleum-degrading seed cultures have been developed for marine settings (Anonymous, 1970; Pacific Northwest Laboratories, 1970), but the effectiveness of some of the agents is in doubt. Atlas and Bartha (1973a) tested two bacterial inocula and found them to be totally ineffective; the rates of crude oil mineralization in the inoculated and control systems were identical and when the cultures were added to sterile sea water, the rates of degradation were slower than in natural sea water. A mutant bacterial culture used to degrade oil at a spill contaminated beach was somewhat effective (McDowell, Bourgeois, and Zitrides, 1980).

Schwendinger (1968) was one of the first to attempt to seed microorganisms onto soil to effect the removal of oil. An inoculum of Cellumonas sp. and nutrients was able to degrade the hydrocarbons more effectively than just the addition of fertilizer alone. Other researchers have met with varying success when seeding microorganisms onto petroleum-contaminated soils. Lehtomaki and Niemela (1975) found that the addition of 10^8 cells/g soil of two hydrocarbon-degrading isolates did not significantly influence oil concentrations. The application of 10^6 oil-utilizing bacteria/cm^2 resulted in a slight additional degradation of the C20 to C25 group of n-saturated compounds (Jobson, et al., 1974). Hunt, et al. (1973) advocated the use of seeding to stimulate the degradation of oil in artic climates where short summers and low soil temperatures may limit the activity and rate of growth of the indigenous population. The addition of 10^4 microorganisms per gram of dry soil was tested as a means of increasing this activity. The inoculum was isolated from a soil taken around oil seeps and enriched with Prudhoe Bay crude oil. The addition of nitrogen and phosphorus at 300 and 100 ppm, inoculation and adjustment of the pH to 7 increased microbial activity over the controls by at least a factor of 4 after 40 days. On the other hand, Westlake, Jobson and Cook (1978) determined that the addition of oil-degrading bacteria to soil of the boreal region of the artic resulted in no increase in the changes of the recovered oil, but this may have been due to insufficient application.

Microbial seeding of soil environments has been applied to the degradation of organics other than petroleum. Inoculation of cultures acclimated to parathion could remove almost all the parathion within 11 days, while in the control, only 14 percent was removed (Daughton and Hsieh, 1977). The acclimated culture could rapidly degrade the parathion at levels up to 5000 ppm in non-flooded soils, and was able to retain this capacity for 8 to 14 days after inoculation onto soils with parathion. Edgehill and Finn (1983) isolated a strain of Arthrobacter (ATCC3379) that could utilize pentachlorophenol as its sole carbon source. In laboratory tests, inoculation of 10^6 organisms per gram of dry soil reduced the half life of the pesticide from 14 days to less than one. Thorough mixing, larger inoculum sizes, and higher temperatures increased the effectiveness of the treatment. A mixed microbial population from primary sewage and another culture containing primarily Pseudomonas were tested to determine their effects on the degradation of formaldehyde and aniline in soil (Wentsel, et al., 1981). This treatment was moderately successful in removing formaldehyde at levels less than 2000 ppm. Aniline was not degraded by the primary sewage inoculum, but was removed when a mixed population acclimated to it was added along with nutrients and yeast extract. Application of microorganisms from sewage effluent was a low-cost, fairly effective method for the removal of water soluble biodegradable organics. The use of adapted mutant cultures to degrade chlordane and dinitrobenzene was only partially effective with some loss of chlordane was noted. The rates of dinitrobenzene loss were accelerated slightly in the chambers inoculated with adapted microbes, but microbial activity was not shown to be the cause.

The addition of adapted mutant microbes was not completely successful in these cases, but has great potential. At least six companies are involved in the production of microbial strains to be used to treat abandoned hazardous waste sites and chemical spills (Anonymous, 1981 and Anonymous, 1982). They have had problems marketing their bacterial products partly due to the number of irresponsible salesmen who once sold enzymes as a potential cure-all. Polybac Corporation's (Allentown, PA) products have been used to reduce formaldehyde levels in the ground from 1000 ppm to under 50 ppm within 50 days, to clean up oil spilled onto surface soils and a beach (McDowell, Bourgeois, and Zitrides, 1980), to treat wastewater containing hazardous organics (Wilkinson, Kelso, and Hopkins, 1978), to restore soils and ground water contaminated by acrylonitrile (Polybac Corporation, 1983), and remove orthochlorophenol which polluted soil and a pond (Anonymous, 1981). O.H. Materials (Findley, OH) has used mutant bacteria to treat incidents involving spills to soils and ground water of acrylonitrile; phenol and its chlorinated derivatives (Walton and Dobbs, 1980); ethylene glycol, propyl acetate and other compounds; dichlorobenzene, trichlorobenzene, and methylene chloride (Quince and Gardner, 1982) and other compounds.

Other companies identified by Anonymous (1981, 1982) which produce mutant bacteria to detoxify soils contaminated with hazardous organics include Sybron Biochemicals (Salem, VA), Flow Laboratories (Englewood, NJ) and General Environmental Sciences (Cleveland, OH). Literature written by the scientists at these companies indicate that their products have been effective in restoring contaminated soils. An oil pollution problem at a fuel transfer depot was treated with the addition of 500 pounds of nutrients, 80 pounds of emulsifier, and rehydrated mutant bacterial degraders along with tilling to provide aeration and thorough mixing (McDowell, Bourgeois, and Zitrides, 1980). An orthochlorophenol spill in Missouri contaminated soil and a pond (Polybac Corporation, 1983). A spray/injection leachate system was built using the pond as a treatment reactor. The pond was seeded with Polybac's products and the concentration of orthochlorophenol fell from 15,000 ppm to less than 1 ppm within nine months. Polybac's products were able to reduce acrylonitrile concentrations from 1000 to 1 ppm within three months following a spill in Ohio. Surface foaming and a spray/leachate recovery system with a portable bio-reactor were employed in this cleanup.

Several factors must be considered before a cleanup system employing acclimated bacteria can be implemented to restore contaminated aquifers. The biodegradability of the contaminants must be assessed; the source, quantity, and nature of the spilled material and the environmental conditions of the site must be considered (McDowell, Bourgeois, and Zitrides, 1980). A laboratory investigation of the kinetics of biodegradation for the acclimated bacteria, the potential for inhibition under various conditions, the oxygen and nutrient requirements, and effects of temperature should be done. The solubility of the contaminant may need to be increased by adding emulsifiers to allow microbial activity on the contaminants. The geology of the site and the extent of contamination must be investigated. The stratigraphy beneath the site and a description of the soils and bedrock should be detailed (Quince and Gardner, 1982). The hydrogeologic data that is needed is formation porosity, hydraulic gradient, depth to water, permeability, ground water velocity and direction, and recharge/discharge information. The quantity and character of the contaminants and their location in the aquifer determines what containment technique, recovery method, and treatment system should be used. The systems which have used acclimated bacteria to restore contaminated aquifers typically have relied on biological wastewater treatment techniques such as activated sludge, aeration lagoons, trickling filters, aerobic digestion, composting, and waste stabilization. Many of the systems recharge the effluent from biological treatment to the aquifer to create a closed loop of recovery, treatment, and recharge. This flushes the contaminants out of the soil rapidly and establishes hydrodynamic control separating the contaminated zone from the rest of the aquifer. Another benefit is that the acclimated bacteria can be added to the aquifer and can act in situ to degrade the contaminant. The recharge water can be adjusted to provide optimal conditions for the growth of the acclimated bacteria and the indigenous populations which may also act on the contaminants.

Several examples illustrate the effectiveness of acclimated bacteria to cleanup contaminated aquifers. An acrylonitrile spill was handled by removing the ground water, treating it with mutant bacteria in a small reactor, and recharging it (Polybac Corporation, 1983). The levels of acrylonitrile fell from 1000 ppm to 1 ppm in three months. For another acrylonitrile spill, the result of a tank car leak (Walton and Dobbs, 1980), the primary treatment was air stripping, but after the levels of acrylonitrile dropped enough to permit microbial growth, mutant bacteria were seeded in the spill site. Following a period of adaptation and growth, the bacteria were able to reduce the levels of acrylonitrile to less than 2000 ppb. After treatment by clarification and air stripping had reduced levels of the spilled organics (including propyl acetate and ethylene glycol) at another site to concentrations less than 200 ppm, bacteria, nutrients, and air were injected into the subsurface (Quince and Gardner, 1982). This method reduced the levels of the contaminants to below that required by the regulatory agencies, with a reduction in the total organic carbon (TOC) from 40,000 to less than 1 ppm. A similar treatment system was used to restore an aquifer contaminated by organics lost from storage tanks. Air stripping and inoculation with hydrocarbon degrading bacteria were able to remove 95 percent of the contamination.

At a site where 130,000 gallons of organic chemicals were spilled, treatment was by clarification, adsorption onto granular activated carbon (GAC), air stripping, and then recharge (Ohneck and Gardner, 1982). Once contamination levels fell below 1000 ppm, a biodegradation program employing faculative hydrocarbon-degrading bacteria, nutrients, and oxygen was initiated. The goal for this portion of the treatment was to establish colonies of bacteria in the vadose zone to degrade the contaminants trapped in the soil. The indigenous bacteria probably were as important or more so for the degradation of the contaminants since laboratory experiments showed that when they were supplied with nutrients they were able to metabolize the contaminants at the same or greater rates than the hydrocarbon-degrading bacteria inocula. Levels of contamination decreased in one set of soil cores from about 25,000 mg/l to about 2000 mg/l in two months. Monitoring wells showed no chemical contamination above the allowable criteria of 1 mg/l at the end of the treatment program. It was concluded that complete cleanup had been achieved and had restored the quality of the aquifer to a level equal to that existing prior to the spill. Shuckrow and Pajak (1981) were less successful in their bench scale studies at a site in Muskegon, Michigan, contaminated by several priority pollutants and at least 70 other organics. The priority pollutants included solvents, degreasers, and vinyl chloride. Attempts to acclimate an activated sludge culture to the new ground water were only minimally successful. A commercial microbial culture was not effective either. However, coupling an activated sludge process with treatment by granular activated carbon proved beneficial since the activated sludge unit removed the organics that passed through the GAC column. Up to 95 percent of the TOC was removed so long as the GAC continued to function well. Microbial growth on the activated carbon may also play a role in the removal of contaminants (Werner, 1982).

CONCLUSIONS

Of the three techniques discussed in this section, enhancement of the native population and withdrawal and treatment seem to currently be the most effective methods for biological restoration of aquifers contaminated by organic compounds. Biostimulation by the addition of oxygen, nitrogen, phosphorus, and other inorganic nutrients has been chiefly used to reclaim aquifers contaminated by gasoline, and has been effective in reducing the quantity of gasoline although not completely eliminating it. Enhancing the indigenous microbial population was also fairly effective in treating organic solvents which contaminated ground water. Although alternative sources of oxygen such as ozone or hydrogen peroxide increase the dissolved oxygen available for microbial activity, they have the disadvantages of being toxic and being largely unproven. Withdrawal and biological treatment of contaminated ground water has been shown to be an effective method for restoration of aquifers. Activated sludge treatment, often in conjunction with physical treatment processes such as activated carbon adsorption or air stripping, has been demonstrated to build up an acclimated microbial population that can degrade the contaminants. While seeding of an acclimated or mutant microbial population holds a great deal of potential since it reduces the period needed for microbial acclimation to what are often recalcitrant substances, results from previous attempts have not proven it to be responsible for the removal of the contaminants. Further work needs to be done to demonstrate that seeding microbes is a viable technique for the restoration of contaminated aquifers.

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SECTION VII

PROTOCOL FOR AQUIFER RESTORATION DECISION-MAKING

The general approach for developing aquifer restoration strategies and selecting the most appropriate one for meeting a given need is, for the most part, intuitively obvious. A logical first step is a preliminary assessment of the nature of the problem. Based on the preliminary assessment, a number of alternative strategies (remedial measures) are developed. From the list of possible alternatives, an optimum would be selected through systematically considering a series of decision factors, environmental impact and cost-effectiveness analysis. Implementation and construction of the chosen alternative would be next, followed by monitoring of the effectiveness of the measure.

The objective of this section is to present a structured protocol that can be followed to develop aquifer restoration strategies. Emphasis is placed on the actual procedure for developing a list of technical alternatives based on appropriate consideration of numerous decision factors. The procedure is not intended to be a set of explicit instructions; rather a general approach which, when modified could be applied to a wide variety of ground water pollution problems. The section begins with a review of pertinent literature; this is followed by information on preliminary activities, and development and evaluation of alternatives.

BACKGROUND INFORMATION

Most of the work in developing structured approaches or protocols for addressing ground water pollution problems has been conducted in response to the Comprehensive Environmental Response, Compensation and Liability Act, P.L. 96-510 (known as CERCLA or "Superfund"). Specifically, Superfund sites require the development of a "remedial action master plan" (RAMP). The purpose of a RAMP is to identify the type, scope, sequence and schedule of remedial projects which may be appropriate in meeting an identified need (Kaschak and Nadeau, 1982). Figures VII.1 and VII.2 are attempts to represent the RAMP process in the form of flow charts. Additionally, Table VII.1 lists the phases of a site contamination and liability audit. Two features are common to all three of these outlines. First, they all have the same general intuitive pattern. Second, they all have provisions for immediate remedial actions to enable the conduction of studies to develop longer-term solutions.

The RAMP is designed as an approach for developing an optimal solution for meeting a given need. Incorporated within the RAMP is the analysis of alternative remedial measures in order to decide on an optimum strategy. The analysis involves consideration of three aspects: (1) environmental impacts; 2) costs; and 3) risks. Risk assessment is an area of study that is now receiving increased attention; Appendix F contains some summary information on risk assessment as related to aquifer restoration. The main problem faced by all risk assessment techniques is that a large portion of the needed information, such as risk pathways or acceptable concentrations, is unknown.

Because ground water cleanup activities are, in general, expensive, considerable interest exists in analyzing costs. St. Clair, McCloskey and Sherman (1982) discuss the advantages and disadvantages of risk

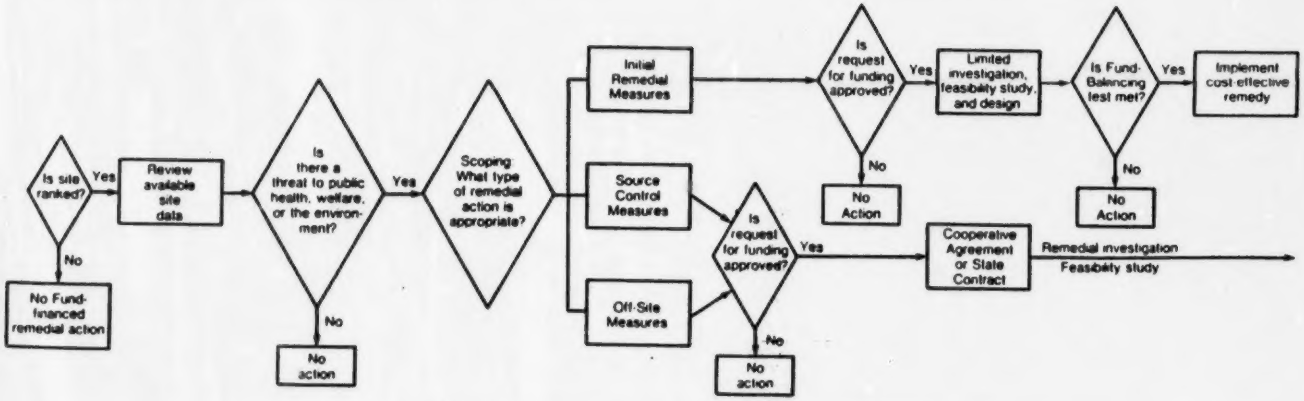
Is site ranked?
Yes
No
No Fund-financed remedial action
Review available site data
Is there a threat to public health, welfare, or the environment?
Yes
No
No action
Scoping What type of remedial action is appropriate?
Initial Remedial Measures
Source Control Measures
Off-Site Measures
Is request for funding approved?
Yes
No
No Action
Limited investigation, feasibility study, and design
Is Fund-Balancing test met?
Yes
No
No Action
Implement cost-effective remedy
Is request for funding approved?
Yes
No
No action
Cooperative Agreement or State Contract
Remedial investigation
Feasibility study

Figure VII.1: Remedial Action Process (Bixler, Hanson, and Langner, 1982).

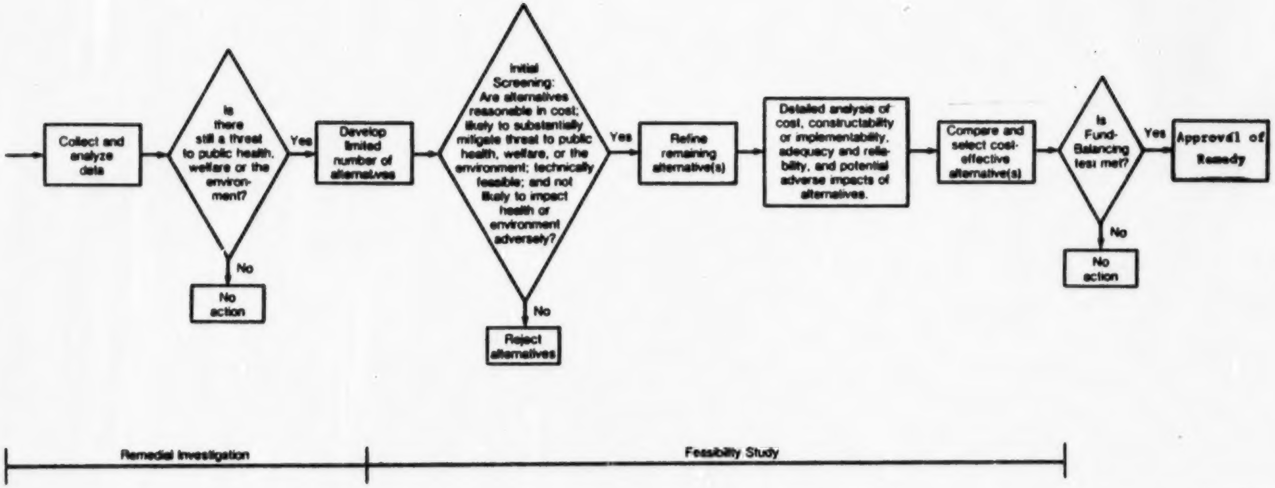
Collect and analyze data
Is there still a threat to public health, welfare or the environment?
Yes
No
No action
Develop limited number of alternatives
Initial Screening: Are alternatives reasonable in cost; likely to substantially mitigate threat to public health, welfare, or the environment; technically feasible; and not likely to impact health or environment adversely?
Yes
No
Reject alternatives
Refine remaining alternative(s)
Detailed analysis of cost, constructability or implementability, adequacy and reliability, and potential adverse impacts of alternatives.
Compare and select cost-effective alternative(s)
Is Fund-Balancing test met?
Yes
No
No action
Approval of Remedy
Remedial Investigation
Feasibility Study

Figure VII.1: (continued)

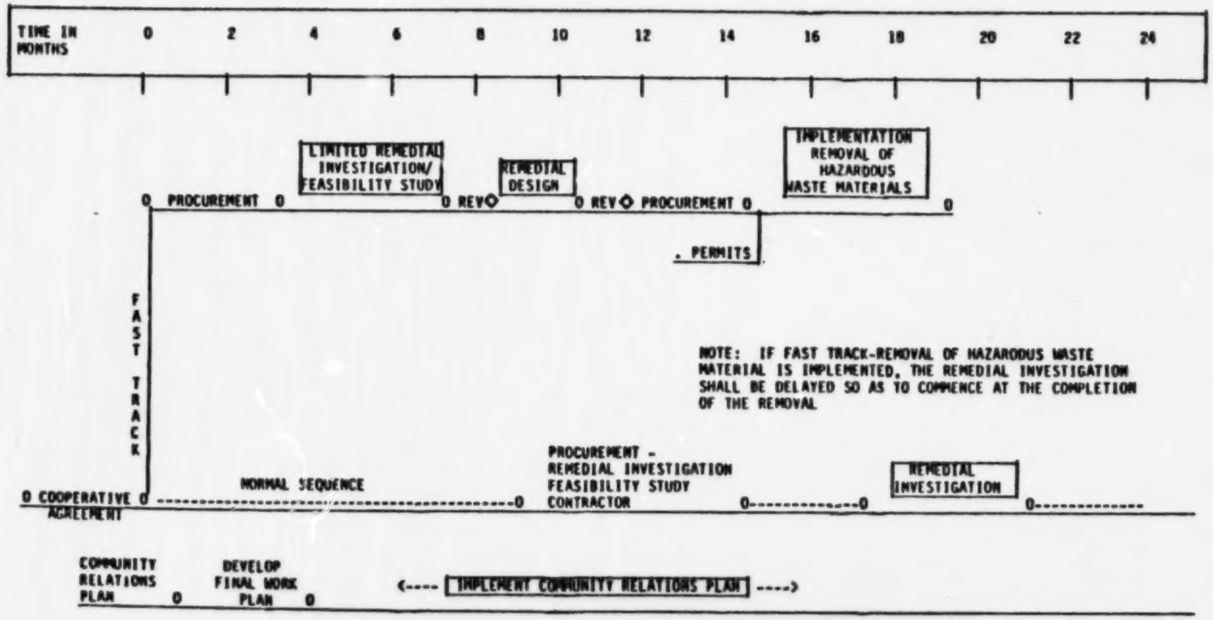

Figure VII.2: Master Site Schedule (Kaschak and Nadeau, 1982).

Table VII.1: Site Contamination and Liability Audit Phased Structure (Housman, Brandwein, and Unites, 1981).

Screening Phases	Phase 1	Initial Property Inventory
	Phase 2	Classification and Identification of Potential Problem Properties
	Phase 3	Preliminary Field Screening
	Phase 4	Prioritization of Problem Properties
Emergency Action Phase	Phase 5	Immediate Emergency Stop Action Response
Detailed Site Investigation and Remedial Phases	Phase 6	Detailed Site Field Investigation
	Phase 7	Definition of Remedial Strategies, Risk and Financial Liability Assessment and Remedial Cost Effectiveness
	Phase 8	Selection of Preferred Remedial Strategy
	Phase 9	Implementation of Remedial Action
	Phase 10	Certification of Performance and Addressing Future Potential Liability Issues

assessment, cost/benefit analysis, cost-effectiveness analysis, decision-tree analysis, trade-off matrices, and sensitivity analysis for alternatives evaluation. Using certain elements of these techniques, they developed a framework for evaluating the cost-effectiveness of remedial actions. Evans, Benson, and Rizzo (1982) describe an integrated, three-phased approach for cost-effective preliminary assessments at hazardous waste sites. Dawson and Brown (1981) have developed an integrated site restoration process, as outlined in Figure VII.3, which includes cost-effectiveness considerations.

CONCEPTUAL FRAMEWORK FOR AQUIFER RESTORATION DECISION-MAKING

Depicted in Figure VII.4 is a flowchart for aquifer restoration decision-making. Each of the steps in Figure VII.4 is discussed in detail in the following sections. Although the general order of the steps in Figure VII.4 is important (and to some degree dictated), it is emphasized that none of the steps are completely independent of the others. Additionally, the procedure is meant to be iterative, thus allowing for refinement in both judgment and design.

Preliminary Activities

Preliminary activities associated with aquifer restoration decision-making include the assemblage of a multi-disciplinary team and problem definition and characterization through the conduction of a preliminary study and evaluation of data and data needs.

Multi-Disciplinary Team

Ground water pollution is not strictly a hydrogeological problem.

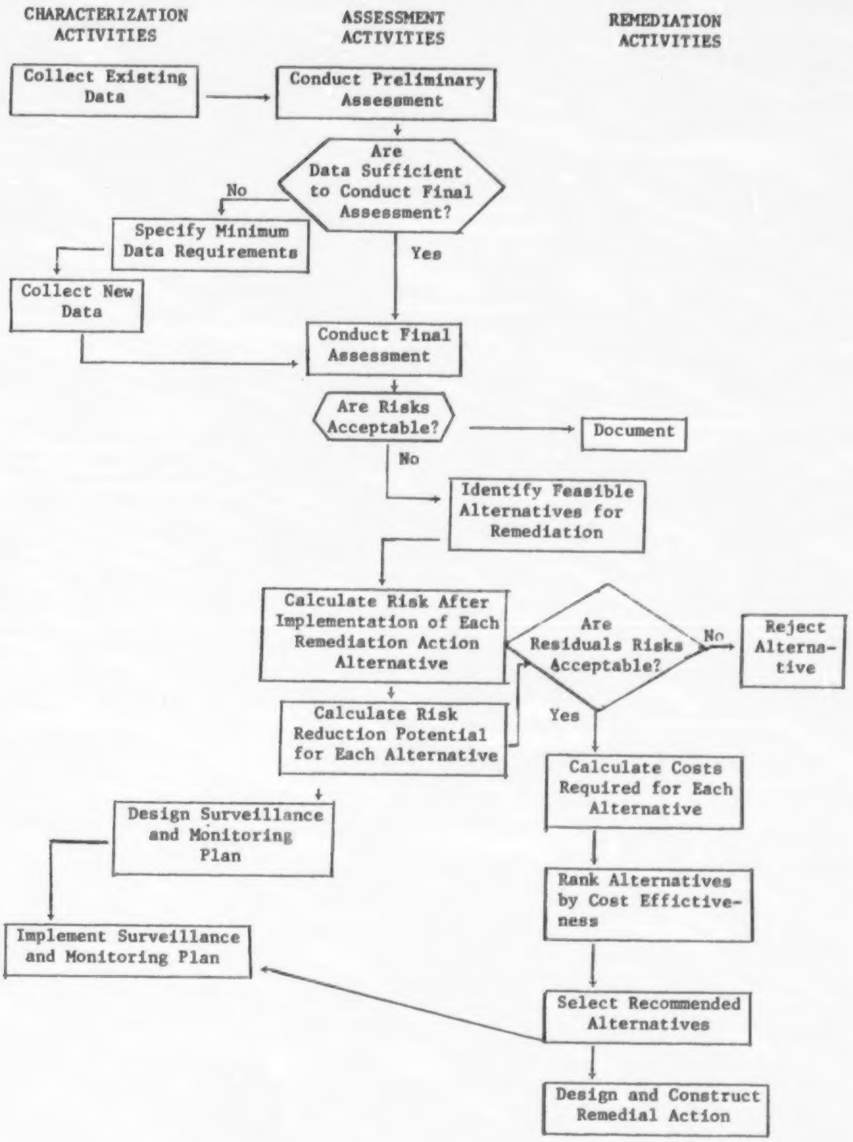
CHARACTERIZATION ACTIVITIES
ASSESSMENT ACTIVITIES
REMEDIATION ACTIVITIES
Collect Existing Data
Conduct Preliminary Assessment
Are Data Sufficient to Conduct Final Assessment?
No
Specify Minimum Data Requirements
Yes
Collect New Data
Conduct Final Assessment
Are Risks Acceptable?
Document
No
Identify Feasible Alternatives for Remediation
Calculate Risk After Implementation of Each Remediation Action Alternative
Are Residuals Risks Acceptable?
No
Reject Alterna-tive
Calculate Risk Reduction Potential for Each Alternative
Yes
Calculate Costs Required for Each Alternative
Design Surveillance and Monitoring Plan
Rank Alternatives by Cost Effictive-ness
Implement Surveillance and Monitoring Plan
Select Recommended Alternatives
Design and Construct Remedial Action

Figure VII.3: Integrated Site Restoration Process (Dawson and Brown, 1981).

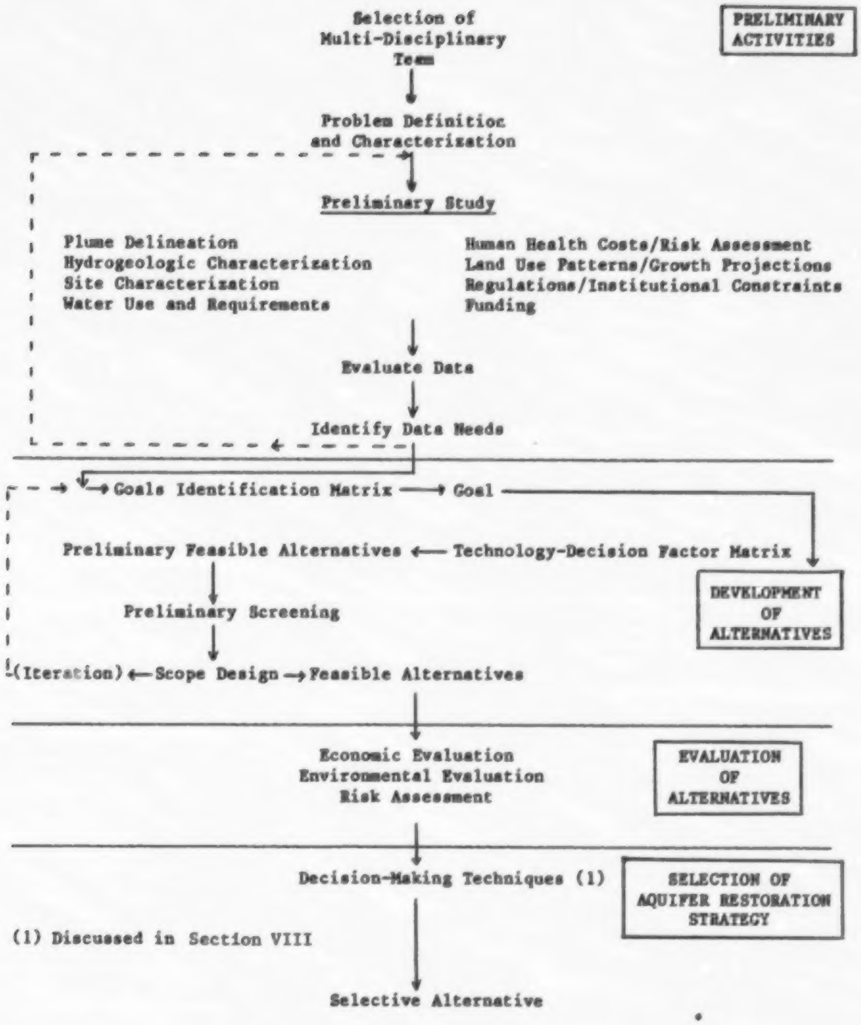
Selection of Multi-Disciplinary Team
PRELIMINARY ACTIVITIES
Problem Definition and Characterization
Preliminary Study
Plume Delineation
Hydrogeologic Characterization
Site Characterization
Water Use and Requirements
Human Health Costs/Risk Assessment
Land Use Patterns/Growth Projections
Regulations/Institutional Constraints
Funding
Evaluate Data
Identify Data Needs
Goals Identification Matrix
Goal
Preliminary Feasible Alternatives
Technology-Decision Factor Matrix
DEVELOPMENT OF ALTERNATIVES
Preliminary Screening
(Iteration)
Scope Design
Feasible Alternatives
Economic Evaluation
Environmental Evaluation
Risk Assessment
EVALUATION OF ALTERNATIVES
Decision-Making Techniques (1)
SELECTION OF AQUIFER RESTORATION STRATEGY
(1) Discussed in Section VIII
Selective Alternative

Figure VII.4: Flowchart for Aquifer Restoration Decision-Making.

The solution to a ground water pollution problem will require involvement from a number of entities and disciplines. Managerial personnel will be involved in the overall planning and development of the project. Technical personnel, both on-site and off-site, will aid in the design of the remedial measure. Remedial-related personnel from the construction industry will have involvement. Also, institutional personnel from different levels of government will almost invariably have involvement. Within each group, a number of different disciplines might be required. For example, the technical personnel required could include hydrogeologists, environmental engineers, soil scientists, microbiologists, chemists, and toxicologists, to name a few. Formulation and implementation of a solution for meeting a particular need will require a multi-disciplinary approach involving a multi-disciplinary team.

Problem Definition and Characterization

The obvious first step in actually dealing with a ground water pollution concern is to define and characterize the problem. The problem will need to be defined in terms of its temporal and areal release patterns, and its urgency for formulating and implementing a solution. The two temporal categories are "anticipated problems" and "existing problems". Anticipated problems most usually will result from planned facilities that have the potential to threaten ground water supplies. The other type of problem is the existing problem. This is the situation where a facility or activity with ground water threatening potential is already in effect. Existing problems can be further subdivided into those that have already degraded ground water, and those that have not yet disturbed ground water but are expected to do so. The approach needed in identifying potential solutions to either of the two types of problems is similar, but because of their "temporal" differences, the proposed solutions may differ significantly.

a. Anticipated Problems

Having identified an anticipated problem, the next step would be to identify the areal release characteristics, and the potential duration and urgency of the problem. The release characteristics of the problem will be directly related to the source. The source, could be a point source (disposal well), an area source (fertilizers in agriculture), a line source (highway deicing salts), or a regional source (increasing number of septic tanks in a region).

The duration of the problem can be classified as either acute or chronic. Will the anticipated problem be short term such as lowering of water levels due to construction dewatering, or will it be a long term problem that will require long term solutions such as a series of injection wells to prevent salt water intrusion?

The urgency of the anticipated problem will be a function of the potential contaminant(s), local hydrogeological characteristics, and the criticality of the threatened aquifer. Anticipated problems usually will have no urgent need for a solution. Ground water pollution potential can be minimized by incorporating certain controls in the design stage.

b. Existing Problems

With existing pollution problems the information needed for characterization it is straightforward. Initial attention should be given to source identification. The contaminant release characteristics and duration of the problem can be characterized as outlined above. The urgency or need for an immediate solution can sometimes be the critical factor with an existing problem. If the polluted aquifer is a source of drinking water, or the problem was discovered due to an adverse public health reaction, there may be a need for an immediate (if only temporary) solution.

A general description of the problem is necessary for defining the scope and extent of further studies and ultimate remedial actions. For example, if a hazardous substance is detected in a water supply well, the immediate solution may be to provide an alternative supply of water. This temporary measure may allow time for study and development of a permanent solution.

Preliminary Study

After identifying an existing or proposed ground water threatening activity or facility, the next effort should be toward further information gathering and more detailed problem characterization. The detail and duration of the preliminary study will be determined by the urgency of the problem and funds available.

The information needs listed below are intended to be comprehensive even though they are described in general terms. Not all information needs will pertain to every problem. Probably the most useful function of these lists will be to aid in developing a list of needed information for specific problems. The following information needs lists are not in any particular order, although some of the needs are dependent on others. An important issue that needs to be considered prior to initiation of any detailed study would be that of funding. Once funding possibilities have been determined, the scope of the analysis can be more appropriately delineated. The other areas of information could probably be approached in groups such as problem specific information (plume delineation and hydrogeologic characteristics) site specific information (site characterization, water use and requirements, and land use patterns and growth projections), and others (human health costs and risk assessment, and regulations and institutional constraints). Should it be decided to go into more than just a cursory review of the problem, sources of information may become a question. Some of the agencies identified in considering regulations and institutional constraints most probably will have information on other issues. Listed in Table VII.2 are some other possible sources of information as related to the different groups.

a. Plume Delineation

Plume delineation is the step in which the amount, nature, and extent of the plume and the source of the ground water pollution is characterized. The information obtained in this step will not only help determine feasible aquifer restoration strategies but may also aid in assessing the possibilities of pretreatment or economic recovery. Information categories of interest are delineated as follows:

Table VII.2: Potential Sources of Information

Group I (problem specific)	Federal or state geological surveys, universities-libraries, geology and engineering departments, state health departments, property owner, county records, well drillers.
Group II (site specific)	Weather bureaus, state water resources boards, census bureaus, soil and water conservation districts, employment commissions, corporation commissions, 208 studies, Department of Agriculture, Forest Service.
Group III (other)	Medical libraries, state or Federal environmental protection agencies, state attorney generals office.

(1) Physical/Chemical Characterization of Pollutant(s) -- A complete physical/chemical characterization of the pollutant(s) is essential. The physical/chemical characterization will determine which surface treatment technology will be required should the pollutant(s) be removed. Some pollutants can be contained by subsurface impermeable barriers, such as slurry walls, while others (those with high ionic strengths) have been shown to actually reduce the impermeability of such structures. A physical/chemical characterization of the pollutant(s) can also give information as to the possibilities for economic recovery, i.e., will the pollutant(s) recovered be salvageable or will it require treatment and disposal? In those cases where a pollutant(s) is anticipated but not yet detected in ground water, a physical/chemical characterization should be done on the known or suspected source of pollution. A physical/chemical characterization of a waste can give an idea as to what pollutants to expect.

(2) Information on Transport and Fate of Pollutants(s) -- Having characterized the pollutant(s) it is then necessary to obtain any and all information on the transport and fate of the pollutant(s) in the subsurface environment. Information on the attenuating capacity of the given soils for the pollutant(s) is important. The behavior of the pollutant(s) under the different pH environments of the subsurface is important in that some pollutants can precipitate or solubilize given the correct conditions. The final outcome of this step should be information on the ability of the particular pollutant(s) to actually migrate through the soil structure and reach the ground water. Feasible mitigation measures will be a function of this ability.

(3) Toxicity and Health Risks of Pollutant(s) -- Information on the toxicity and health risks of the pollutant(s) relative to not only humans but livestock and vegetation should be obtained. The ultimate use of the polluted ground water will be a function of its toxicity and health risks. For example, an aquifer that contains high concentrations of heavy metals will have to be abandoned from further use, while one that has elevated nitrate concentrations might be usable for irrigation with minimal treatment. Specifically, information should be obtained on toxic levels of the pollutant(s) perhaps in the form of a standard. It is also desirable to obtain information on the actual side effects of toxic levels of the pollutant(s), i.e., does it cause temporary acute discomfort; is it a potential carcinogen; are the effects long term or life threatening?

(4) Areal Extent, Depth, Amount of Pollutant(s) -- If possible, an estimate of the areal extent, depth, and amount of

pollutant(s) in the subsurface environment needs to be obtained. The objective is to obtain an estimate of the magnitude of the problem. The "size" of the problem to be rectified, in itself, may limit the number of feasible solutions. Ideally, data from existing monitoring wells, well logs, etc., should be used to estimate the magnitude of the problem. However, this information is often not available. In most cases an "educated guess" of the magnitude of the problem will have to be made by considering broad data such as soil types, topography, climate, and duration of the problem.

An important set of information pertinent to plume delineation is the identification and characterization of the source of pollution. The source will not always be readily identifiable and might require extensive field surveys to be determined. Once the source has been identified, information specific to it should be obtained. These information categories are as follows:

(1) Physical/Chemical Characterization of Source -- As mentioned previously, a complete physical/chemical characterization of a waste might be needed in order to predict potential pollutants. However, this information can also be used for reducing the problem at the source. A physical/chemical characterization can aid in assessing the possibilities for waste pretreatment, in-place stabilization of the waste, recycling, or some other form of economic recovery.

(2) Variability of the Wastes -- The variability of the wastes must be considered in order that a pollutant specific mitigation strategy is not implemented for a highly variable waste. A highly variable waste source would include a landfill that accepted both hazardous and non-hazardous constituents. Other highly variable waste sources, which are quite common today, are those situations in which records of exactly what was disposed do not exist. When the materials which have been disposed cannot be identified, it is difficult to design anything but a general, all-inclusive type of cleanup measure.

(3) Time Factors -- Information on the time of existence of the waste source is also needed. Data on the period a waste source has been in existence can give insight to the magnitude of the problem. Specifically, it is desirable to know how long a given waste has been in-place, or how long a certain activity has been operating.

(4) Previous Waste Disposal Practices -- It is important to know historical information on the practice of waste disposal at the source. Was the waste indiscriminantly dumped and covered, or were there certain precautions taken? The feasible solutions to the problem of leachates from an abandoned open dump may differ from those of a sanitary landfill with a leaking liner. Specifically, information is needed on the exact disposal practices, the length of these operations, any special ground water protection strategies employed, and any or all daily records.

b. Hydrogeologic Characteristics

Assemblage of information on the hydrogeologic characteristics of a site is essential for a successful aquifer restoration program. In essence, this step involves characterization of the subsurface where the problem exists. Subsurface characterization serves two main purposes. First, a description of the hydrogeologic characteristics of the site will allow for a better understanding of the magnitude of the problem. A thorough hydrogeologic investigation will not totally delineate the limits of the problem, but it will aid in estimating the transport and fate of the pollutant in the subsurface. Second, a thorough hydrogeologic investigation will aid in identifying and designing potential aquifer restoration strategies. Information from this step will also be valuable in the plume delineation step. Some areas of needed information and reasons for their interest are as follows:

(1) Geologic Setting and Generalized Soil Profiles -- Determination of the types of soils is important for determining both the capacity of the pollutant(s) to move through the subsurface and the feasible restoration measures. Certain soils will possess higher tendencies to attenuate the pollutant(s) (through adsorption, precipitation, filtration, etc.) than others. Likewise, certain soils will be amenable to certain restoration strategies while others are not.

(2) Soil Physical/Chemical Characteristics -- Once a general soil type has been identified, it is then necessary to characterize this type both physically and chemically. Physical characterization of the soil type will provide information on the ability of the soil to filter the pollutant(s). The physical characterization will also give an idea as to the "workability" of the soil for different cleanup measures. Chemical characterization will provide information on the ability of the soil to chemically remove a given pollutant through adsorption, precipitation, etc. In some cases, the chemical composition of the soil will be needed to determine the feasibility of a particular cleanup strategy, especially in-situ technologies.

(3) Depth to Ground Water and Bedrock -- The depth to ground water in conjunction with the soil physical/chemical characterization will give insight as to how long it will take a pollutant(s) to actually reach the aquifer, if in fact it will. If sufficient depth to the ground water exists in a highly attenuating soil, minimal ground water pollution can be expected. The depth to bedrock is needed to assess the feasibility of some pollutant containment strategies such as slurry walls, grout cutoffs, or sheet piles.

(4) Ground Water Flow Patterns and Volumes -- The flow patterns and volume of ground water threatened will play a vital role in determining the feasible solutions to the problem. Obviously the direction of flow will dictate the actual physical placement of any proposed cleanup measures. Similarly the volume of water affected will dictate the scope of potential cleanup measures.

(5) Recharge Areas and Rates -- Identifying recharge areas and rates will play an important role in aquifer protection plans. The use of institutional measures (such as zoning) to minimize ground water threatening activities in aquifer recharge areas is one such plan. Information on recharge areas and rates for the case of an existing problem will be important for a number of reasons. First, it should be determined whether or not the source(s) is in a recharge area. Solutions to problems located in recharge areas will most likely be more elaborate than those not located in recharge areas, and should include source removal if possible. Second, recharge rates will give insight into the rate of pollutant(s) movement and pollutant(s) dilution.

(6) Aquifer Characteristics -- Identification of aquifer characteristics will be essential for any analysis of ground water flow and pollutant transport. This information becomes extremely important if ground water modeling studies are to be initiated. Listed in Table VII.3 are some of the

Table VII.3: Aquifer Characteristics

confined-unconfined	hydraulic conductivity
isotropic-anisotropic	dispersion coefficients
homogeneous-non-homogeneous	specific yield (storage coefficient)

characteristics that need to be determined, either through the use of extant data or the conduction of field studies.

(7) Existing Monitoring Well Locations and Procedures -- Identification of existing monitoring well locations and the parameters monitored can save both study time and costs.In addition to providing immediate data, existing monitoring wells can, in some cases, become permanent parts of a monitoring network or converted to removal wells.

(8) Background Water Quality Data -- Background water quality data is important in determining the severity of the problem and the appropriate remedial actions.

c. Site Characterization

A description of the general characteristics of the site of the problem is also an important step. Because surface attributes of the site will directly and indirectly affect the subsurface environment, these attributes need to be identified. Information is needed on the climatic factors of precipitation, temperature, and evapotranspiration. Locational factors for which information is needed include topography, accesibility, site size, proximity to surface water, and proximity to population centers. Additional comments on each of these factors are as follows:

(1) Precipitation -- Precipitation in most cases will dictate both the amount and rate at which pollutants from a site "leach" to the ground water. This is especially true for pollutants leaching from solid waste disposal areas. Precipitation also affects the recharge rate of an aquifer.

(2) Temperature -- Surface temperature will become an important factor in determining the feasibility of certain surface treatment strategies. For example, the transfer of organics from ground water in an air-stripping operation will be affected by temperature.

3. Evapotranspiration -- The amount of water lost to the atmosphere through transpiration and evaporation can be important when considering the ultimate use of a site.

For example, surface capping of a landfill relies in part on evapotranspiration from the vegetative cover to reduce the amount of water infiltrating to the solid waste.

(4) Topography -- The general topography of the site will affect the infiltration rate and the feasible solutions. Areas of steep gradients will have little infiltration and will be subject to high erosion rates. This could be important when designing surface disposal sites.

(5) Accessibility -- Related to topography is the accessibility of the site. Areas of rugged terrain or limited access will present not only construction problems but could also hamper any subsequent operation and maintenance activities.

(6) Site Size -- The size of the site refers to the actual surface areal extent of the problem. This factor will affect the feasible solutions in that many of the technologies are size specific. For example, soil removal is probably not economically feasible for a multi-acre contaminated site.

(7) Proximity to Surface Water -- Locations of surface water relative to the site are important for a number of reasons. First, the solution to the ground water problem should not create a surface water problem. In addition, schemes that involve surface treatment may require surface discharge. A location for this discharge needs to be determined. Second, water may play an important role in the construction (slurry walls) and/or operation and maintenance (revegetation) of a site. A source of water may be vital to the success of a given restoration scheme.

(8) Proximity to Population Centers -- The location of the nearest population center relative to the site will help determine both the magnitude of the problem and the potential solutions. If the site is located near a large population center supplied by a well field, the problem may be more urgent than one located in a relatively isolated area.

d. Water Use and Requirements

Determination of current ground water usage and future requirements in the study area will aid in determining the criticality of the threatened or polluted ground water resource. Categories of information needed and the reasons for their importance are as follows:

(1) Current Use -- Information on the amount of water used for domestic, agricultural and industrial purposes should be obtained. Furthermore, this information should be divided into those uses supplied by surface water and ground water. Specifically, information on the amount of water withdrawn from the aquifer in question and what it is used for, should be obtained. This information could become critical should abandonment of the aquifer be considered.

(2) Future Use -- An estimate of predicted future water requirements for domestic, agricultural and industrial purposes should also be obtained. Those areas anticipating large scale growth accompanied by high water demands may need to cleanup existing ground water problems and institute aquifer protection measures (institutional measures).

(3) Current/Future Water Quality Standards -- Beneficial Use Standards -- Procurement of currently available or proposed future beneficial use standards for local ground water could play an important role in determining a feasible aquifer restoration strategy. More specifically, beneficial use standards may dictate the degree of treatment polluted ground water must receive before subsequent use.

(4) Costs -- An estimate of the current costs of supplying water is needed, especially the costs of obtaining ground water from the aquifer under study. The costs associated with changing sources of supply should also be estimated. If changing to a different source of water supply becomes prohibitively expensive, it may be necessary to consider some more elaborate treatment schemes for restoring the aquifer.

e. Human Health Costs and Risk Assessment

An assessment of risks and human health costs associated with the polluted ground water is desirable. Having identified the toxicity and health hazards of the given pollutant during the plume delineation step, an assessment needs to be made of the actual potential for human health impacts. This step is essential in evaluating the alternative of taking no action on aquifer restoration. Examples of needed information are as follows:

(1) Potential Health Problems -- From the plume delineation step there should be information on the health problems associated with the given pollutant(s). Specifically, information is needed on whether the pollutant is a toxicant, carcinogen, or threat to the general health of the population.

(2) Risk Assessment -- Assessing the risks of illness is desirable. Obviously, if a certain water is in violation of a given health or water supply standard the risk is high. The question of interest here is what are the risks of using a potentially polluted yet acceptable (in accordance with the standards or lack thereof) water supply? Ideally, it would be desirable to have quantitative information on the number and frequency of health incidents to be expected. A more feasible solution would be to assign a subjective probability of occurrence for different levels of contamination.

f. Land Use Patterns and Growth Projections

The objective of this information-gathering step is to insure that potential restoration strategies do not become exercises in futility. Specifically, it would be unwise to spend millions of dollars cleaning up a particular problem that is just one of many currently or potentially polluting a given aquifer. Useful information in this regard includes current and future land use patterns and activity growth in the study area. Examples of needed information are as follows:

a. Current Land Use Patterns -- A determination of the existing land use patterns will give considerable insight into the type and degree of treatment a particular problem should be given. The percentage of land devoted to urban, rural and industrial uses in and around the site should be determined. A removal and treatment system in a highly industrialized area could lead to one group removing, treating and paying for pollution it did not cause.

b. Growth Projections -- A projection of growth in activities that possess the potential for degrading ground water is essential. If a certain ground water formation is already degraded in quality, and the projections for future growth include increased activity in the area, then containment rather than cleanup may be desirable. Listed in Table VII.4 are some of the more immediate ground water threatening activities which should be explored.

g. Regulations and Institutional Constraints

A key step in any aquifer restoration strategy is to identify institutional constraints and enforcement programs. A variety of regulatory agencies for ground water quality control may exist within a given state, and determining who is in charge may be somewhat of a problem. Identification of all constraints and enforcement agencies is necessary so that a proposed solution satisfactory to one agency does not violate the requirements of another agency. Examples of necessary information in this regard are as follows:

(1) Regulatory Agencies -- As early as possible the regulatory agencies in charge of ground water quality should be identified. Areas of interest pertaining to ground water would include monitoring of ground water, waste disposal and construction permitting, and enforcement of standards.

(2) Standards and Guidelines -- All pertinent water quality and effluent standards should be obtained. In addition, some states might have standards or guidelines for waste disposal facilities, minimum construction standards, siting of specific facilities, or required environmental studies.

(3) Legislation -- There has been a good deal of recent environmental legislation which could apply to a wide variety of ground water pollution problems. Thorough knowledge of pertinent legislation will not only provide goals and guidelines for mitigation measures, but may also provide insight as to possible sources of funding. For example, consideration should be given to the requirements of the Resource Conservation and Recovery Act (RCRA), the Surface Mining Control and Reclamation Act (SMCRA), the "Superfund" program (Comprehensive Environmental Response, Compensation and Liability Act - CERCLA) for hazardous waste disposal facilities, and the Safe drinking Water Act for "sole source" aquifers. In addition, review of current state legislation would be warranted.

Table VII.4: Examples of Ground Water Threatening Activities

Industrial landfills and impoundments
Municipal landfills
Septic tanks
Mining, minerals extraction, petroleum production
Agricultural chemicals

h. Funding

Probably the biggest obstacle to be overcome in any aquifer restoration program will be funding. In simple terms, cleaning up ground water can be a very expensive venture. Not only are the technologies expensive to implement and operate, but they may be difficult to design. If questions arise over who will pay for the cleanup (as they often do), the pollution problem may end up in litigation, thus adding to the expense and delaying the implementation of aquifer restoration strategies. These delays exacerbate the problem and escalate the costs. A preliminary review of the availability of funds should most probably be done immediately after identification of the problem. Based on the availability of funds, the scope of the study can be determined. If sufficient funds are not available, detailed analysis and design will probably have to be foregone for a small-scale aquifer management or policy analysis.

One of the key funding issues is related to responsibility for cleanup costs. The pattern to date has been for the suspected polluters to balk at accepting responsibility for a given case of ground water pollution. The case then goes to litigation and the suspected polluter, if found guilty, will often file bankruptcy rather than accept the immense financial burden associated with ground water pollution cleanup. This leaves the state or Federal government with the satisfaction of having identified the polluter, but lacking in terms of a responsible party for cleaning up. This type of arrangement is not the most desirable for both sides and should be avoided if possible. The fact that legal recourse can be taken should be recognized, but an effort towards joint cooperation is more desirable.

Data Evaluation

A critical aspect of the information gathering step will be evaluating the quality of the information gathered. Kaschak and Nadeau (1982) list three issues to be concerned with once available information has been gathered as: (1) how good is the data today; (2) can an engineering solution be properly developed and designed; and (3) will the data be defensible in court? Consideration of the age of the information, sampling and analysis protocols, and the chain of custody of the information can aid in assessing whether or not the information is accurate and/or useful.

Data Needs

Having completed the gathering and evaluation of available information, the next step is to identify those areas where the search for information was unsuccessful. Kaschak and Nadeau (1982) identify this as the most difficult step, i.e., to decide what additional information is necessary to be able to identify and evaluate alternative restoration strategies without "studying the site to death". Information voids should be identified and categorized. One categorization scheme is as follows:

(1) Criticality -- The relative importance needs to be considered for each of the individual data gaps. It would probbly not be justified to put as much effort into obtaining "regional population growth patterns" as that of obtaining "toxicity" information for the pollutants of concern. Some type of priority ranking should be assigned to the missing

information. Chapter VIII describes several techniques which could aid in this ranking.

(2) Availability -- For each of the information gaps consideration should be given to whether or not the information is obtainable. For example, records of disposal at a landfill are desirable but are not always kept. If these records are not available, there is no way of obtaining them. Conversely, background water quality data may not be presently available but is certainly obtainable through the drilling of monitoring wells. In those cases where the information is not obtainable, it could be excluded from the decision-making process or a best estimate could be developed and utilized.

(3) Time -- Certain information may be obtainable, but only after extended periods of time. The background water quality data mentioned previously is certainly obtainable, but monitoring should occur over a period of time. Conversely, certain aquifer characteristics can be obtained in just a few days. If the problem being studied is of an emergency nature, then data that requires long periods of time to gather should be considered non-obtainable.

(4) Costs -- For all the information voids, consideration must be given to the cost of searching for and/or acquiring that information. Obviously, an estimate of aquifer characteristics from soils and geological maps will be less expensive than extensive monitoring networks.

After the information gaps have been categorized under the above headings, decisions can be made as to desirability and necessity of filling the gaps. If the information-gathering process alone will exceed the funding, the study may have to be abandoned or re-directed.

DEVELOPMENT OF ALTERNATIVES

The development of alternatives stage of the aquifer restoration decision-making process shown in Figure VII.4 can best be described as an interative process. The goals for addressing the established need should be delineated, and potential technological approaches for meeting the goals/need should be identified. These potential approaches (strategies or alternatives) should be screened and scope designs developed for potentially feasible alternatives. This process may require several iterations as additional information is developed.

Definition of Goals

The term "restoration" seems to imply that any ground water remediation activity will attempt to return the aquifer to its original condition. Although desirable, this is not always feasible. Therefore, a subjective decision to be made in any aquifer restoration program is related to the "goal" of the program. Specific strategies to achieve the goal(s) will be dictated, for the most part, by physical, chemical and monetary constraints.

This decision-making process includes four different goals: prevention; abatement; cleanup; and restoration. Prevention, as the name implies, means that pollution is not allowed to occur. The context of "prevention" herein will be taken to mean "not allowing pollutants to reach ground water". Abatement means "to put an end to". Hence, abatement of ground water pollution will include the "cessation of pollutants moving into the ground water, and the curtailment of the movement of pollutants having already reached the ground water". Cleanup refers to "elimination of pollutants through removal and treatment or in-situ immobilization or treatment". Restoration will include those measures that attempt to return the aquifer to its original state. This most often will involve a cleanup strategy plus recharge of treated or fresh water. It should be noted that these goals are not totally independent of each other. More specifically, a truly effective "cleanup" strategy may also include "prevention" and "abatement" steps. Table VII.5 contains a listing of various strategies (detailed in Sections IV, V and VI) available for obtaining various goals.

The definition of the goals of a ground water management strategy does not represent a totally isolated evaluation. In some instances, the goals may be limited by problem-specific conditions. Thorough review of the results of the preliminary activities shown be undertaken prior to establishment of goals.

Goals Identification Matrix

Table VII.6 is a goals identification matrix. The possible goals are listed along with some decision factors and conditions under which the goals might be appropriate. Review of the limiting factors for each of the possible goals will enable a more rapid identification of feasible and obtainable goals for an identified need. Not all possible influencing factors have been listed in Table VII.6. Each identified need will have its own influencing factors which should be considered in the selection of the specific goal(s).

Technology-Decision Factor Matrix

Having identified a preliminary goal for an identified need, the technology-decision factor matrix in Table VII.7 can be utilized. The technology (technologies) that can be considerd for achieving various goals are identified in the first two columns. After identifying the feasible technology (technologies), the decision factors and conditions under which the technology might be applied can be reviewed from the remaining columns in Table VII.7. The end result should be a series of

Table VII.5:Potential Aquifer Restoration Strategies for Chronic Pollution Problems

Goal	Strategy Type	Action
Prevention	Institutional Measures	1. Aquifer or effluent standards, effluent charges or credits, land zoning.
	Source Control	1. Source reduction or removal 2. Optimum site selection 3. Man-made control options a. Impermeable membranes b. Impermeable materials c. Surface capping d. Collector drains e. Interceptor trenches
Abatement	Waste Management	1. Modification of pumping 2. Removal Wells 3. Pressure ridges 4. Subsurface barriers
Cleanup	Waste Treatment and Disposal	1. Above-ground treatment 2. In-situ methods
Restoration	Cleanup Plus Recharge	

Table VII.6: Goals Identification Matrix

Goals	Temporal Situation	Funding Costs	Water Use Requirements	Hydrogeological Characteristics
Restoration	Restoration is a possible goal when considering existing problems.	Restoration schemes are the most expensive management strategies. However, restoration will also have the added benefits of returning the aquifer to a beneficial use.	Restoration should be the primary goal when dealing with ground water that is or will be the main source of water supply for a given area.	Restoration is most feasible for shallow, unconfined aquifers of originally high quality water.
Cleanup	Cleanup is a goal when considering existing problems.	Cleanup strategies are expensive. Sometimes the aquifer can be returned to a beneficial use and there is also the possibility for economic recovery from certain pollutants.	Cleanup should be considered when the ground water serves a beneficial use other than human consumption such as agricultural or industrial purposes.	Cleanup measures are most feasible for shallow ground water sources, but do have some applicability to deeper, confined sources by removal and treatment.
Abatement	Abatement can be considered when dealing with existing problems and can also be included as a safeguard for future facilities or anticipated problems.	Abatement strategies range from moderate to very expensive with little chance for economic recovery.	Abatement measures are usually employed to save the unpolluted portions of an aquifer while conceding the polluted portion as lost.	Abatement measures are most applicable to shallow sources with cessation being the most applicable abatement measure for deep resources.
Prevention	Prevention measures are only applicable to future facilities or anticipated problems	Prevention strategies range from low to moderately expensive with little chance for economic recovery.	Prevention measures should be applied to protect any currently used or potentially useable ground	No restrictions

Table VII.6: (continued)

Goals	Areal Extent	Human Health Risks	Land Use Patterns
Restoration	As the size of the problem increases the attractiveness of the restoration schemes decreases due to increased costs. Problems of regional nature most probably will be amenable to abatement measures.	If human health risks are high, restoration or cleanup should be given top priority if technically feasible. If not technically feasible, abandonment and development of new source should be considered.	Restoration and cleanup measures should not be given high priority in areas that are or will continue to be subjected to ground water quality stresses such as industrial waste disposal areas.
Cleanup	Cleanup measures are not economically attractive for small, localized problems and do have economies of scale for larger problems. However, if the problem becomes extremely large, such as regional, these economies of scale disappear.	See above.	See above.
Abatement	The abatement measures to be employed are size specific and cover the whole range from very small, localized problems to large, regional problems.	For low to moderate health risks abatement measures can be employed to prevent further degradation of an aquifer.	Abatement measures are the most attractive alternatives for ground water pollution control in areas subjected to continued threats if anything at all is to be done.
Prevention	Physical prevention measures are size specific. Some institutional measures are applicable on a regional level.	No restrictions.	No restrictions.

technologies or technology combinations that are potentially applicable for meeting an identified need. Table VII.7 is not totally comprehensive since there are many additional decision factors associated with each of the listed technologies. However, Table VII.7 does have general utility in that major decision factors are outlined. Additionally, Table VII.7 should trigger information exchange among members of the multi-disciplinary team. The team could develop an expanded version of the technology-decision factor matrix specific to the identified need under examination.

Preliminary Screening

Having developed a preliminary list of feasible technologies (alternatives), a preliminary screening process can be used to narrow the choices. The preliminary screening process will necessarily rely heavily on professional judgment, however, listed below are some factors that should be considered:

(1) Technical Feasibility -- The technical feasibility of all potential alternatives should be considered. Some technologies have been widely used and their success documented; others are still in the early stages of development, or at least their application to ground water pollution control has been limited. Another consideration would be the technical capabilities of the personnel that are to design and operate the proposed technology. Some technologies are complex in design and require extensive monitoring for successful operation and maintenance. If trained personnel will not be available to handle these responsibilities, perhaps a more passive system should be considered.

(2) Public Acceptance -- One important aspect of any aquifer restoration scheme will be its acceptance by the public. If the proposed solution will involve surface "eyesores" or highly technical operational requirements, it might be difficult to gain the acceptance of the general public.

Table VII.7: Technology-Decision Factor Matrix

Technology	Management Strategy and Complementary Technologies	Temporal Situation	Pollutant Type	Areal Extent
Institutional Measures	Implementation of institutional measures will most probably be for the prevention of ground water pollution but could also be used as abatement measures.	Applicability to existing problems is probably minimal except for orders to cease a given activity. Widest application is for preservation of current high quality ground water.		
Source Control Strategies	Source control measures are most applicable as preventive techniques, however, they are often incorporated as part of overall cleanup measures at uncontrolled sites.	Source control strategies are applicable to existing problems and should be included in the design of all future disposal facilities.	No restrictions.	No restrictions.
Well Systems	Well systems are applicable to all management strategies including restoration. Well systems in all cases require complementary technologies, usually surface treatment and discharge.	Well systems are applicable to both existing and anticipated problems and have been used to control emergency situations in certain cases.	Well systems are applicable to any pollutant that flows with or on top of the ground water.	Well systems are probably not economically feasible for small, localized pollution sources. Conversely, for large sources of pollution well systems may become uneconomical in that they by necessity draw in both polluted and nonpolluted water.
Interceptor Systems	Interceptor systems can be employed for cleanup, abatement or prevention of ground water pollution. However, in all cases a complementary technology is required, usually in the form of surface treatment and discharge.	When dealing with existing problems, interceptor systems will take the form of interceptor trenches, while anticipated problems are usually prevented by employing collector drain systems. There is some applicability of interceptor trenches to emergency spills involving floating hydrocarbons.	Interceptor systems are applicable to any pollutant that flows with or on top of the ground water.	Interceptor systems are feasible for small, localized pollution sources.
Surface Water Control	Surface water control technologies are most often used as preventive measures but can also be used as part of abatement schemes.	Surface water control can be applied to existing problems as part of an overall abatement scheme and should be considered in the design of all future land disposal facilities.	Surface water control is applicable to most any pollutant, however, the possibility of gas production should be considered when designing "surface capping" measures for organic wastes.	No restrictions.
Impermeable Liners	Liners are usually placed on a site prior to the initiation of a given activity, hence they are most applicable as prevention steps. Liners themselves are not totally effective and are usually used in conjunction with surface water control, source control, or underdrain systems.	The applicability of liners to existing problems is limited in that it usually involves removal of the waste or polluted soil.	Some asphaltic and treated soil liners become more permeable upon exposure to leachates. Some synthetic liners show poor resistance to hydrocarbons.	Because installation of liners involves excavation and specialized construction, economies of scale occur for larger problems. However, if the size of the problem is more than 5 to 10 acres, liners may become uneconomical due to material costs.

Table VII.7: (continued)

Technology	Management Strategy and Complementary Technologies	Temporal Situation	Pollutant Type	Areal Extent
Sheet-piling	Sheet-piling follows the attributes of grouting and slurry systems in that its most practical applications will be for abatement and prevention of ground water pollution. However, the number of cases where sheet-piling will be the best technology is minimal.	Sheet-piling is similar to grouting. Probably the most applicable situation will be as emergency measures for containment of spills.	Sheet-piles are generally corrosion resistant.	As the size of a project increases, sheet piling will become uneconomical because of high material and shipping costs.
Grouting	Grouting is similar to slurry systems in that it will often require complementary technologies to accomplish restoration or cleanup. Grouting can be individually applicable as an abatement measure.	Grouting is also a versatile technology in that it has wide application to both existing and anticipated pollution problems. In addition grouting is being promoted as a procedure for containing emergency spills.	Grouts containing bentonite clay are subject to limitations similar to those for slurry systems. Additionally, chemical grouts are not successful in highly acidic or alkaline environments.	Costs for grout cutoff systems are high, hence they will be applicable to small localized cases of pollution.
Slurry Walls	Slurry walls can only be parts of overall restoration or cleanup schemes. Slurry walls are individually applicable as abatement measures, however, some sort of ground water removal system is usually included. Slurry walls are also individually applicable as prevention measures, but once again are usually used in conjunction with other measures.	Slurry walls are very versatile in that they can be applied to existing problems as abatement measures or they can be incorporated in the design of future facilities for prevention of ground water pollution. Slurry walls are probably not applicable to emergency situations such as spills.	Slurry systems are sensitive to specific pollutants, especially those of high ionic. strength.	Slurry systems are more applicable to larger problems. Slurry systems become more economical as the "length to depth" ratio increases.
Surface Treatment	Surface treatment technologies can be used in systems designed to prevent, abate, cleanup or restore polluted aquifers. Treatment technologies will always require some sort of pollutant removal system.	Surface treatment can be used for acute and chronic cases of ground water pollution. Treatment can be used at existing sites and at anticipated problems in a preventive mode.	No restrictions.	Surface treatment has both upper and lower size limitations. Surface treatment can be too elaborate for small sources yet uneconomical for extremely large areas.
In-Situ Treatment	In-situ treatment technologies can be used in systems designed to abate, cleanup or restore polluted aquifers. In-situ technologies will always require some sort of nutrient/chemical injection system.	In-situ technologies can be applied to both acute and chronic cases of existing pollution. The application of in-situ technologies for treatment of anticipated problems is not possible.	In-situ treatment is extremely pollutant specific. Biological methods are applicable mainly to organics and chemical methods are applicable mainly to synthetic compounds.	Same as for Surface Treatment.

Table VII.7: (continued)

Technology	Soils	Aquifer Characteristics	Site Characteristics	Regulations
Institutional Measures				
Source Control Strategies	No restrictions.	No restrictions.	Since most source control strategies will involve surface activities, the site should be readily accessible.	
Well Systems	Well systems require soils that readily transmit ground water and any associated pollutants.	Well systems are amenable to most aquifer types, however, they may not be ideal for extremely shallow aquifers (<5 m.).	Sites must be accessible to drilling equipment. Well systems usually will require monitoring and a receiving source for their discharge. If the removed water requires treatment the site should be accessible to or in the proximity of surface treatment facilities.	
Interceptor Systems	Interceptor systems require fairly loose, pervious soils that readily transmit ground water and any associated pollutants.	Areas with high water tables or high impervious soils or rock layers are desirable.	Because the collected water will need to be removed, treated, and discharged, the site should be readily accessible.	
Surface Water Control	Surface water control measures are applicable to any soil. Surface capping becomes economical when there exists native clays readily available.	No restrictions.	Regrading to maximize runoff is an important aspect. Hence areas with extreme topographic relief should probably be considered less desirable.	
Impermeable Liners	Soils do not limit the application of liners, except when native clays are to be used as the liner. In this case the soils should be of sufficient impermeability and sufficient thickness.	Very high water tables may limit the use of liners in that they may cause the system to "float".	The site should be accessible to a variety of construction vehicles, including some specialized liner installation machines.	Some states now have regulations governing the in-place characteristics which a liner must possess.

Table VII.7: (continued)

Technology	Soils	Aquifer Characteristics	Site Characteristics	Regulations
Sheet-piling	Pile driving requires a relatively uniform, loose, boulder-free soil for ease of construction.	Sheet-piling will be limited to shallow (<100 ft.) aquifers.	Similar to those for slurry systems except the operation is not water intensive.	
Grouting	Grouting is limited to granular types of soils that have a pore size large enough to accept grout fluids under pressure yet small enough to prevent significant pollutant migration before implementation. Grouting in a highly layered soil profile may result in incomplete formation of grout envelope.	Presence of high water tables and rapidly flowing ground water limits groutability due to dilution of grouts and rapid transport of contaminants.	Similar to those for slurry walls.	Some grouting procedures are proprietary and some chemicals may be controlled under the Underground Injection Program.
Slurry Walls	Slurry systems are applicable to most all soil types. However, in loose soils such as sand or gravel there can be significant losses of slurry which may make the system uneconomical.	Slurry systems are generally applicable to shallow (<150 ft.) aquifers.	Sites with general accessibility, moderate topographic relief and a ready source of water are most desirable Construction of slurry systems is an equipment intensive operation which requires large amounts of water.	Some construction procedures are patented and will require a license.
Surface Treatment	No restrictions.	No restrictions.	On-site surface treatment will require extremely accessible sites that can adequately handle construction traffic and equipment. Once built, surface treatment facilities will only occupy a finite space, but will have to remain accessible for monitoring activities.	
In-Situ Treatment	Most probably applicable only to permeable soils which will readily accept injected materials.	Shallow aquifers are probably more desirable.	Same as for well systems.	

(3) Physical Constraints -- Some of the potential alternatives might be eliminated by obvious physical constraints. For example, placement of impermeable barriers might not be feasible in a densely populated area.

Scope Design

Probably the best means of eliminating possible but non-feasible alternatives would be through the use of a scope design. The scope design is a small-scale analysis of the proposed alternatives for preliminary estimates of size, costs, life expectancy, efficiency, etc. The scope design will rely on estimates or rules-of-thumb figures for costs, and other factors to generate an approximation for each of the potential alternatives. The scope design will be less expensive, less time consuming, and inherently less accurate than a complete engineering and hydrogeological analysis. The objective of the scope design should be to eliminate the obviously too expensive or too land-intensive alternatives.

Iteration

With preliminary size and cost data from the scope design, an iteration through the procedure outlined above would be appropriate. Perhaps the data generated might indicate that all the possible alternatives exceed the available funding. In this case, it might be necessary to redefine the goals of the ground water management strategy, and attempt to develop new possible technologies for achieving these modified goals. The objective of iteration is to further narrow the list of potential alternatives to those that are economically and technically feasible.

EVALUATION OF ALTERNATIVES AND SELECTION OF AQUIFER RESTORATION STRATEGY

Selection of a single alternative from the list of feasible alternatives should come from balanced consideration of technical, economic and environmental factors. A philosophy often quoted and generally accepted is that the "most inexpensive remedial action that reduces risks to an acceptable level can be considered the most cost-effective" (St. Clair, McCloskey and Sherman, 1982). This statement raises a number of issues such as:

(1) What is an acceptable level?

(2) Acceptable to whom?

(3) Is the most cost-effective the optimum?

(4) Are there environmental implications in addition to economic and risk implications?

(5) Are cost and risk equally important?

(6) Are confidence levels the same for cost and risk calculations?

The structure of this section will be to discuss methodologies for and issues associated with evaluating alternatives based on their economic, environmental and risk implications. Chapter VI presents some decision-making techniques for integrating these evaluations and developing an optimum strategy.

Economic Considerations

General statements concerning the costs of aquifer restoration are difficult to make. One widely accepted statement is that the cost of cleaning up a polluted aquifer is extremely expensive. This is true for many but not all cases. Expense can be considered relative and not all ground water remediation activities are designed with cleanup as the ultimate goal. Difficulties arise in any attempt to quantify or collate information on the costs of aquifer restoration. First, minimal detailed cost data is being or has been reported. This is due in part to the confidentiality and litigation associated with many ground water pollution problems. Additionally, the data that have been reported show an extremely wide range, are highly problem specific, and sometimes are estimates at best.

The fact that ground water cleanup costs exhibit a wide range can be exemplified by citing some examples. Kaufmann (1982) has shown that removing TCE and other organic compounds from the water supply of a small New Jersey city can be accomplished for under $140,000 per year using granular activated carbon. Neely, et al. (1981), on the other hand, have estimated the cost of cleaning up ground water at a site polluted by industrial solvents and acid sludge to be over $7 million. Hittman Associates (1981) have preliminarily assessed the cleanup of ground water polluted from abandoned lead and zinc mines in northeastern Oklahoma to be in excess of $20 million.

The cost of a ground water remediation activity is second in importance only to public health concerns. The technologies for cleaning polluted ground water exist, but may not be economical. In a recent study, Neely, et al. (1981) found that cost was the prime determinant of the type of remedial technology employed at uncontrolled hazardous waste sites. Since elaborate cleanup schemes are expensive, companies may have opted for less expensive but environmentally-more threatening prevention and abatement measures.

Any ground water cleanup activity will require funding for feasibility and engineering studies, construction, operation and maintenance, and other costs. Any one of these areas can become a major cost factor. For example, Roux Associates recently began a $1 million study just to develop a list of recommendations for remedial actions at Massachusetts toxic waste sites. In contrast, Kaufmann (1982) has shown operating costs to be the major cost component of a granular activated carbon cleanup system.

The generic assignment of costs to various aquifer restoration technologies (strategies) is difficult. Individual technologies can vary in cost depending on the type of pollutant, nature of the aquifer, the ultimate goal of the technology, and many other factors. A good deal of work has been done in assessing the costs of various components of individual technologies. For example, extensive information has become available on the cost of installation and operation of monitoring wells. Monitoring wells should be an integral part of any aquifer restoration technology. Minning (1982) provides a cost comparison for five different drilling methods. Rehtlane and Patton (1982) examine the economic tradeoffs of multiple port versus standpipe piezometers. Ward (1982) examines the costs of in-situ leach wells for uranium extraction. As noted in Section IV, Campbell and Lehr (1977) give an excellent discussion of the costs of completing wells under a variety of geological conditions.

There have been several recent studies to assign unit costs, or at least comparative cost figures, for some of the physical measures for minimizing, abating or controlling ground water pollution. Rishel, et al. (1983) have estimated costs for remedial response actions at two types of uncontrolled and abandoned hazardous waste disposal sites. Table VII.8 is a listing of costs for a landfill site, and Table VII.9 summarizes costs for a surface impoundment site.

Tolman, et al. (1978) developed a summary of estimated costs and characteristics of remedial methods for a hypothetical, single size (10-acre) landfill; the summary is shown in Table VII.10. Additionally, some qualitative comments can be made concerning some of the technologies listed in Table VII.10. First, surface water control technologies are usually only used as preventive and/or abatement measures when dealing with ground water pollution. Hence, these operations will require some complementary technology to cleanup an aquifer. Of the four ground water control technologies listed in Table VII.10, a bentonite slurry trench must be considered the most cost-effective. Construction of grout curtains is slow, labor intensive and expensive, and as such this process is probably only economically feasible only small, localized cases of pollution. The plume management strategies listed in Table VII.10 all will incur long-term operating and maintenance costs. These costs are associated with manpower to oversee operations, power supplies for pumps, and possibly accelerated maintenance due to the nature of pollutants being pumped (Glover, 1982). Also, the passive management systems (drains, interceptor trenches) generally have lower operating costs than the active (pumped) systems.

In summary, most of the work to date in the area of costs of aquifer restoration technologies has been in developing data for the components of the technologies. Minimal information has been reported

Table VII.8: Average U.S. Low and High Costs of Unit Operations for Medium-Sized Landfill Sites (Rishel, et al., 1983)

Unit Operations	Unit	Average U.S. Cost $ Per Unit*				Total Units Used**
		Initial Capital		Life Cycle Costs		
		Low	High	Low	High	
Contour grading and surface water diversion	Site area, ha	15,300	17,900	16,300	19,900	5.4 ha site area
Bituminous concrete surface sealing	Site area, ha	67,300	92,700	67,300	92,700	5.4 ha site area
Revegetation	Site area, ha	3,450	16,500	14,300	18,100	5.4 ha site area
Bentonite slurry trench	Wall face area, m²	54.5	96.1	61.2	103	10,800 m² wall face area
Grout curtain	Wall face area, m²	600	1,209	937	1,880	10,800 m² wall face area
Sheet piling cutoff wall	Wall face area, m²	73	108	73	108	10,800 m² wall face area
Grout bottom sealing	Site area, ha	5,282,000	10,209,000	5,296,000	10,224,000	5.4 ha site area
Drains	Pipe length, m	72.7	106	357	416	260 m pipe length
Well point system	Intercept face area, m²	62.5	105	107	153	2,000 m² intercept face area
Deep well system	Intercept face area, m²	11.6	18.3	28.6	37.2	4,800 m² intercept face area
Injection	Intercept face area, m²	77	90	1,760	1,785	550 m² intercept face area
Leachate recirculation by subgrade irrigation	Site area, ha	5,270	8,360	19,700	24,000	5.4 ha site area
Chemical fixation	Site area, ha	69,100	130,000	82,500	145,000	5.4 ha site area
Chemical injection	Landfill volume, m³	1.67	3.28	2.16	3.81	150,000 m³ landfill volume
Excavation and reburial	Landfill volume, m³	116	120	116	120	596,000 m³ landfill volume
Ponding	Site area, ha	647	1,028	647	1,028	5.4 ha site area
Trench construction	Trench length, m	12.2	14.34	15.11	20.32	930 m trench length
Perimeter gravel trench vents	Trench length, m	99.2	144	100	146	935 m trench length
Treatment of contaminated ground water	Contaminated water, L/d	1.52	2.57	2.52	4.38	440,740 L/d contaminated water
Gas migration control - passive	Site perimeter, m	161	241	168	256	935 m site perimeter
Gas migration control - active	Site perimeter, m	113	173	167	279	935 m site perimeter

* Mid-1980 dollars, 10-year life cycle, O & M costs are discounted at 11.4% to present value, capital costs are not amortized.

** For 5.4 ha site.

Table VII.9: Average U.S. Low and High Costs of Unit Operations for Medium-Sized Surface Impoundment Sites (Rishel, et al., 1983)

		Average U.S. Cost $ Per Unit*				
		Initial Capital		Life Cycle Costs		
Unit Operations	*Unit*	*Low*	*High*	*Low*	*High*	*Total Units Used***
Pond closure and contour grading of surface	*Site area, ha*	*26,900*	*35,100*	*35,900*	*53,500*	*0.47 ha site area*
Bituminous concrete surface	*Site area, ha*	*48,500*	*70,700*	*48,500*	*70,700*	*0.47 ha site area*
Revegetation	*Site area, ha*	*2,540*	*3,820*	*3,970*	*5,450*	*0.47 ha site area*
Slurry trench cutoff wall	*Wall face area, m²*	*60.1*	*106*	*60.1*	*106*	*4,165 m² wall face area*
Grout curtain	*Wall face area, m²*	*326*	*631*	*343*	*649*	*4,104 m² wall face area*
Sheet piling cutoff wall	*Wall face area, m²*	*76.8*	*115*	*94.6*	*135*	*4,100 m² wall face area*
Grout bottom seal	*Site area, ha*	*868,000*	*1,621,000*	*1,024,000*	*1,792,000*	*0.47 ha site area*
Toe and underdrains	*Pipe Length, m*	*316*	*609*	*1,550*	*1,960*	*60 m pipe length*
Well point system	*Intercept face area, m²*	*62.3*	*117*	*321*	*398*	*300 m² intercept face area*
Deep well system	*Intercept face area, m²*	*33.2*	*60.3*	*114.4*	*149*	*950 m² intercept face area*
Well injection system	*Intercept face area, m²*	*31.3*	*55.5*	*109*	*141*	*950 m² intercept face area*
Leachate treatment	*Contaminated water, L/d*	*1.16*	*1.96*	*4.49*	*8.14*	*51,870 L/d contaminated water*
Berm reconstruction	*Replaced berm, m³*	*2.98*	*3.80*	*4.00*	*5.85*	*410 m³ berm*
Excavation and disposal at secure landfill	*Impoundment volume, m³*	*260*	*268*	*260*	*268*	*5,000 impoundment volume*

** Mid-1980 dollars, 10-year life cycle, O & M costs are discounted at 11.4% to present value, capital costs are not amortized.*

*** For 0.47 ha impoundment.*

Table VII.10: Summary of Estimated Costs and Characteristics of Remedial Methods (Tolman, et al., 1978)

Method	Average Estimated Costs * ($ in Thousands)	Characteristics/Remarks
		Surface Water Control
Contour Grading	184	Increases runoff, reduces infiltration.
Surface Water Diversion	20	Diverts surface water from fill.
Surface Sealing		
Clay (14-46 cm (6-18 in.))	234	If locally available, native clay is economical means of retarding infiltration.
Bituminous Concrete (4-13 cm (1.5-5 in.))	315	Rapid coverage; can eliminate infiltration.
Fly Ash (30-60 cm (12-24 in.))	235	Material may leach metals; may be available free.
PVC (30 mil)	482	Very impermeable; expensive seal; careful subgrade preparation is necessary.
Drainage Field (if required)	65	Carries infiltrated water off seal; increases effectiveness of seal.
Revegetation on Slopes <12 percent	10	Stabilizes cover material; seasonally increases transpiration; provides aesthetic benefit.
on Slopes >12 percent	19	
		Groundwater Control
Bentonite Slurry Trench	670	Simple construction methods; retards groundwater flow.
Grout Curtain	1,400	Very effective in permeable soils.
Sheet Piling	800	Widely used for shoring.
Bottom Sealing	4,000	Leachate collection may be needed, acts as a liner; difficult drilling through refuse.
		Plume Management**
Drains	23	Effective in lowering water table a few meters in unconsolidated materials; can be used to collect shallow leachate.
Well Point Dewatering	185	Suction lift limits depth to 7-9m (20-30 ft); inexpensive installation; uses only one pump; can be used to collect shallow leachate.
Deep Well Dewatering	183	Used in lowering deep water tables; one pump needed per well; high maintenance costs.
Injection/Extraction Barrier	199	Creates a hydraulic barrier to stop leachate movement; operation and maintenance costs are high.
Spray Irrigation	366	Spreads leachate over the landfill for recycling; potential odor problem.
At-grade Irrigation	32	Gated pipe with ridge and furrow irrigation; potential odor problem; recycles leachate.
Subgrade Irrigation	28	Large-scale drainage field; recycles leachate.
		Chemical Immobilization
Chemical Fixation of Cover	145	Uses chemically fixed sludge to provide a top seal; provides means of disposal for sludge; helps stabilize landfill.
Chemical Injection	86	Immobilizes a single pollutant; in most cases not feasible.
		Excavation and Reburial
Excavation and Reburial	4,570	Very expensive; difficult construction.

*Costs for hypothetical 4-hectare (10-acre) landfill. High and low estimates were averaged to determine these costs.

**Costs include present worth of 20 years, operation, maintenance, and, where applicable, power for 4-hectare (10-acre) landfill.

in terms of costs of overall aquifer restoration strategies. Most studies will require the analysis of individual cost components as outlined in the following section.

Economic Evaluation

Economic evaluation of feasible alternatives can follow the traditional procedure of itemizing all the costs for a given project, ammortizing these costs for the life of the project, developing measures of the benefits of the project, and comparing these data for each of the alternatives. A number of unique concerns arise when considering an economic evaluation of ground water contamination problems.

The first major concern is associated with the comparison of alternatives on a common basis. Two alternatives may be projected to achieve the same result through radically different methods. Relevant issues under this heading are as follows:

(1) The first issue is the level of treatment or efficiency of the system. One alternative might reduce the contaminant concentration to parts per billion, another to parts per million. Is the increased reduction in concentration needed and/or economically justifiable?

(2) Some alternatives may be operation- and maintenance-intensive while others, providing the same solution, might be less intensive. Comparison of these types of alternatives is difficult due to constantly changing interest rates.

(3) Alternatives providing similar solutions might have radically different time frames or life expectancies. All projects should be compared on a common project period. Bixler, Hanson and Langner (1982) have identified this period to be the lesser of: the period of potential exposure to the contaminated materials in the absence of remedial action; or 20 years.

The second major concern is the cost of specific items associated with alternatives. It is important that all cost items be identified.

As an example of how extensive these lists can be, Table VII.11 summarizes the cost components for a well system (Lundy and Mahan, 1982). Bixler, Hanson and Langner (1982) note that cost items can be monetary and non-monetary, direct or indirect. In addition to the obvious direct monetary costs such as materials, equipment, etc., non-monetary costs must be included such as relocation costs, loss of revenues, decreased property values and others. It is important that the list of cost items be complete and include all pertinent costs (Thorsen, 1981).

Another concern associated with the economic evaluation of alternatives is that of developing a measure of the benefits of an alternative. Some benefits will be very difficult to assign dollar values, for example, reduced health risks. Additionally, some benefits may be hard to quantify, much less assign dollar values.

The final and most important issue associated with economic analysis is the generic approach to be utilized. St. Clair, McCloskey and Sherman (1982) analyzed the advantages and disadvantages of various approaches, including risk assessment, cost-benefit analysis, cost-effectiveness analysis, trade-off matrices, and sensitivity analysis. Utilizing the positive attributes of these approaches, St. Clair, McCloskey and Sherman (1982) have developed a framework for evaluating cost-effectiveness of remedial actions at uncontrolled hazardous waste sites. Table VII.12 displays an example trade-off utilizing the developed framework.

In summary, there exists no ideal methodology for economic evaluations of aquifer restoration strategies. The best approach is to

Table VII.11: Cost Components of Well Systems (Lundy and Mahan, 1982)

Cost Component	Cost Element	Principal Factors Affecting Cost
Plume Delineation (K)*	Soil borings Monitor wells Data analysis Laboratory analysis Reporting	Plume area and depth Complexity of hydrogeology
System Design (K)	Consulting fees Computer time	Complexity of hydrogeology Size of containment system
Well System (K)	Construction engineering Well construction Materials	Plume size Aquifer flux Transmissivity
Surface Infrastructure (K)	Access roads Power transmission Piping	Plume size Configuration of wells
Treatment Facility (K)	Construction engineering Treatment system	System discharge Composition/concentration of recovered water
Well System (O&M)	Pump operation (power) System maintenance	Aquifer flux/pumping depth Fluid corrosivity
Treatment Facility (O&M)	Chemicals Labor Power	System discharge Composition/concentration of recovered water
Monitoring	Sampling Analysis Reporting	Complexity of system

*K denotes capital costs; O and M denote operation and maintenance costs.

Table VII.12: Example Trade-Off Matrix for Cost-Effectiveness Assessment of Remedial Actions at Uncontrolled Hazardous Waste Sites (St. Clair, McCloskey, and Sherman, 1982).

	Cost Ratings				**Generic Effectiveness Measures**								**Site-Specific Effectiveness Measures**					
Alternatives	Construction	Operation & Maintainence	Other	**Σ Cost Ratings**	Level of Cleanup/ Isolation Achievable	Time to Achieve Clean-up/Isolation	Technology Status	Usability of Land After Action	Capability of Action to Minimize Community Impacts During Implementation	Capability of Action to Minimize Adverse Health & Environmental Impacts During Implementation	Risk of Failure	Impact of Failure	Ability to Minimize Impact on Adjacent Residents	Usability of Downstream Lake After Action			**Σ Effectiveness Ratings**	**$\frac{\Sigma \text{ Effectiveness Ratings}}{\Sigma \text{ Cost Ratings}}$**
Weighting Factors																		
Encompassing Slurry Wall with Cap																		
Downgradient Slurry Wall with Extraction Wells, Treat with Carbon																		
Extraction Wells, Treat with Carbon																		
Extraction Wells, Treat with Biox																		

develop a modified version of an existing methodology that is applicable to the problem of concern. The methodology utilized should have the following basic attributes: (1) it compares alternatives on a common basis; (2) it possesses some measure of assessing benefits; (3) it is comprehensive and considers all relevant factors; and (4) its results are replicable and are not subject to bias.

Environmental Evaluation

Each of the proposed alternatives must also be analyzed for their potential impact on the environment. There are a variety of approaches that can be used to assess these impacts, including empirical assessment methodologies, interaction matrices, network analyses, checklists, and others (Canter, 1977). The purpose of this section is to identify the need for environmental impact assessment in aquifer restoration projects, and to identify some unique issues associated with it.

The first unique issue to be identified in association with ground water cleanup activities is that some alternatives may represent "an irretrievable committment of natural resources", i.e. some alternatives may require that the aquifer remain permanently altered. This is especially true of technologies such as impermeable barriers (slurry walls, grouts). Secondly, because the unique aspects of ground water remediation activities usually lie underground, the above ground consequences of the remedial action should be relatively easy to assess. More specifically, ground water remedial actions for the most part, do not represent large, land intensive undertakings. Depending on the technology employed, there will exist a potential to affect several environmental categories. Examples include air quality, surface water quality, and noise. There should exist ample information on related activities so that the assessment of the above-ground impacts of ground water remedial actions is simple, straightforward and less time-consuming than the assessment of subsurface effects.

The last issue associated with environmental evaluation is the importance of public participation. Because of the recent attention afforded ground water pollution episodes by the media, the public has become ill-informed and frightened. It is desirable to avoid public histeria in any project, and this is especially true for aquifer restoration projects. Because ground water is a "hidden resource", improving the public understanding may be especially difficult. Careful planning and increased attention should be applied to the role of public participation in any aquifer restoration studies. Freudenthal and Calender (1981) note that public participation programs promote conflict resolution by providing opportunities for individuals and opposing groups to explore compromise solutions. Detailed information on public participation in aquifer restoration decision-making is included in Appendix E.

Risk Assessment

Cornaby, et al. (1982) stated:

> "The paramount concern is that no known general methodology is available for conducting overall environmental risk assessment, risk assessment that includes both humans and especially non-human or ecological receptors. In fact, the terminology in the literature is not always clear, suggesting that our views and knowledge of environmental risk assessment are still evolving."

This statement should serve as adequate notice that assessing the risks of aquifer restoration alternatives will not be easy. Berger (1982) states that risk assessment has been defined as, "the identification of hazards, the allocation of cause, the estimation of probability that harm will result, and the balancing of harm with benefit". Moreover, Berger (1982) states that selecting an effective remedial technique involves the balancing of the need to contain contaminants within acceptable levels against the costs associated with the cleanup measures. St. Clair, McCloskey and Sherman (1982) state that "a risk assessment involves the definition of the risks to the environment and human health of continued pollution from a site" and "the most inexpensive remedial action that reduces the risk to an acceptable level could be considered the most cost-effective". Dawson and Sanning (1982) note that the objective of a remedial action is to reduce associated risks to an acceptable level.

The most important question associated with risk assessment is--"how can the risks of aquifer restoration alternatives be assessed"? There are two generally accepted approaches to risk assessment. The first approach is to utilize criteria or standards for a pollutant and work backwards, utilizing intrinsic properties of the pollutant and aquifer, to develop a list of possible alternatives. The second approach is to analyze the effectiveness of various alternatives and compare their resultant concentrations with a given standard. No matter which approach is used, a "criteria" or "standard" or "acceptable level" is involved and these data, for the most part, are non-existent. Dawson and Sanning (1982) outline a method for setting site restoration criteria by using air or water standards and working backwards with data on dilution potential and distribution characteristics. This methodology is dependent on existing criteria for other environmental media and knowledge of transport mechanics, which may not be available.

Several risk assessment techniques have been developed for assessing the risk of hazardous waste sites. With slight modifications, some of these would be applicable to assessing different alternatives at individual sites. Unterberg, Stone and Tafuri (1981) outline such a procedure for assessing spill sites. Caldwell, Barrett and Chang (1981) have developed a ranking system for the release of hazardous substances. Nelson and Young (1981) discuss a location and prioritization scheme for future investigation of abandoned dump sites. Unites, Possidento and Housman (1980) describe the development of a site investigation manual for risk assessment. Kufs, et al. (1980) have developed a methodology for selecting sites for investigation based on their adverse environmental impacts. Berger (1982) describes a general methodology for assessing risks based on a similar approach as Kufs, et al. (1980). This methodology considers four characteristics: receptors, pathways, waste characteristics, and waste management practices. Additional information on risk assessment and risk assessment techniques is in Appendix F.

Nisbet (1982) discusses some uses and limitations of risk assessments. Nisbet (1982) and Berger (1982) both point out that without detailed analytical monitoring programs, risk assessments can usually only produce a qualitat[illegible] ranking of alternatives. Nisbet (1982) also points out that risk assessments are difficult to conduct and give uncertain results, because: (1) exposure is usually variable and poorly characterized; (2) toxicity information is hard to extrapolate to humans from animals; and (3) ground water transport mechanics are often unknown, thus making the population at risk difficult to estimate.

In summary, risk assessment could be the most difficult aspect of evaluating aquifer restoration alternatives. The problems to be encountered stem from the fact that most of the needed information for any comprehensive methodology will not exist. The use of estimations in any methodology will limit its replicability.

The best approach to risk assessment will be to develop a methodology suited to the identified need. Modification of existing risk assessment techniques is one approach. The best risk assessment technique will be one that best utilizes available information and requires the least amount of estimated input.

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SECTION VIII

TECHNIQUES FOR DECISION-MAKING

Numerous decisions are required in the selection of an aquifer restoration strategy for meeting a given need. Examples of required decisions include those related to selection of containment options, ground water treatment processes and design, and site closure options. Alternatives exist for each required decision, and the selection of the most appropriate one for meeting a given need can be a difficult task. The alternative with the greatest potential for meeting a given need will most likely not be the least environmentally damaging, least costly, and least risky. Therefore, trade-off analysis typically includes importance weighting of decision factors and the evaluation of a set of alternatives relative to each factor. Although the methodologies outlined in this section have found their greatest application in environmental impact studies, they can be utilized for decision-making related to aquifer restoration strategies.

Importance weighting is done in every decision related to the selection of an aquifer restoration strategy. For example, decisions are made on the relative importance of existing environmental resources, the importance/significance of anticipated beneficial and detrimental environmental impacts, monetary costs, and public acceptability. In most cases, this weighting is done via informal, ad hoc approaches without using available formalized techniques to provide a documented record of the considerations and rationale. Professional judgment is involved in both ad hoc and formalized approaches.

The extent to which a set of alternative strategies and combinations thereof are evaluated relative to a series of decision factors depends upon the number of strategies being evaluated and the nature and extent of the study. Thorough studies involving multiple alternatives (strategies) will tend to give greater emphasis to the comparisons of alternatives. Comparisons of alternatives are often made on an ad hoc basis in the absence of quantitative information on the alternatives, and without using available structured techniques to provide a documented record of the considerations and rationale. Again, as was the case for importance weighting, professional judgment is involved in both ad hoc and structured approaches.

The primary focus of this section will be on the principles and practice of importance weighting in decisions related to the selection of an aquifer restoration strategy for meeting a given need. Briefer information will be presented on techniques for evaluation of alternatives relative to a series of decision factors. The reason for this balance is that importance weighting requires more judgment and has greater influence on the final selection than does the evaluation of alternatives. This is not to say that the latter is unimportant, but simply to indicate that more attention should be given to fundamental importance weighting techniques. This section begins with a conceptual framework for trade-off analysis and is followed by examples of both informal and structured approaches for importance weighting. The ranking/rating/scaling of alternatives are also briefly addressed followed by information on the development of a decision matrix.

CONCEPTUAL FRAMEWORK FOR TRADE-OFF ANALYSIS

Trade-off analysis typically involves the comparison of a set of alternatives relative to a series of decision factors. For example, for clean-up of a polluted aquifer there may be several treatment processes which could be used, including both in-situ options and treatment following pumpage to the surface. Factors related to these alternatives can include the health risk, economic efficiency, social concerns (public preference), and bio-physical, cultural and socio-economic impacts (both beneficial and detrimental impacts should be considered). Table VIII.1 displays a trade-off matrix for systematically comparing specific alternatives relative to a series of decision factors. The following approaches can be used to complete the trade-off matrix:

(1) qualitative approach in which descriptive information on each alternative relative to each decision factor is presented in the matrix;

(2) quantitative approach in which quantitative information on each alternative relative to each decision factor is displayed in the matrix;

(3) ranking, rating, or scaling approach in which the qualitative or quantitative information on each alternative is summarized via the assignment of a rank, or rating, or scale value relative to each decision factor (the rank, or rating, or scale value is presented in the matrix);

(4) weighting approach in which the importance weight of each decision factor relative to each other decision factor is considered, with the resultant discussion of the information on each alternative (qualitative; or quantitative; or ranking, rating, or scaling) being presented in view of the relative importance of the decision factors; and

(5) weighting-ranking/rating/scaling approach in which the importance weight for each decision factor is multiplied by the ranking/rating/scale of each alternative, then the resulting products for each alternative are summed to develop an overall composite index or score for each alternative.

Table VIII.1: Trade-off Matrix

	Alternatives				
Decision Factor	1	2	3	4	5
Health Risk					
Economic Efficiency					
Social Concerns (public preference)					
Environmental Impacts					
-- Biophysical					
-- Cultural					
-- Socio-economic					

Decision-making which involves the comparison of a set of alternatives relative to a series of decision factors is not unique in terms of its application to environmentally-oriented problems such as aquifer restoration. This approach represents a classic decision-making problem which is often referred to as multi-attribute or multi-criteria decision making. The conceptual framework for this type of decision-making appeared in the early 1960's in the U.S. Department of Defense. Since that time it has been applied to numerous situations requiring decisions, including those which involve consideration of environmental factors and impacts.

Two decision factors listed in Table VIII.1 are health risk and social concerns (public preference). Public participation programs for determining public preference are highlighted in Appendix E. One approach addressing health risk involves risk assessment, and Appendix F provides information on using risk assessment in decisions related to remedial actions for polluted ground water.

IMPORTANCE WEIGHTING FOR DECISION FACTORS

If the qualitative or quantitative approach is used for completion of the matrix as shown in Table VIII.1, information for this approach relative to economic efficiency environmental impacts can be found in Sections IV through VI. It should be noted that this information would also be needed for the approaches involving importance weighting and/or ranking/rating/scaling. If the importance weighting approach is used the critical issue is the assignment of importance weights to the individual decision factors, or at least the arrangement of them in a rank ordering of importance. Table VIII.2 summarizes some structured importance weighting or ranking techniques which could be used to achieve this step. These techniques have been used in numerous environmental decision-making projects. Brief descriptions of several reference sources and techniques from Table VIII.2 will be presented later as illustrations of the techniques. In addition to the structured techniques, less-formal approaches such as reliance on public participation programs can also be used as the basis for importance weighting.

SYSTEMATIC COMPARISON OF STRUCTURED IMPORTANCE WEIGHTING TECHNIQUES

As shown in Table VIII.2 there are a number of importance weighting techniques which can be used in decision-making related to aquifer restoration strategies. As would be expected, there are advantages and limitations to specific structured importance weighting techniques. One study to compare six techniques was conducted by Eckenrode (1965). To insure that the research results would be useful in a variety of situations where comparative judgments are required, three different judgment situations were used, one in each of three experiments:

(1) A specific air defense system development, where the judges were six persons who had personally conducted analytical studies on the system in question and were thoroughly familiar with it. They judged the relative importance of six carefully defined system criteria frequently found in military air defense system specifications: economy, early availability, lethality, reliability, mobility, and troop safety.

(2) A general (hypothetical) air defense system development, where the 12 judges used were familiar with the problems of air defense system design and use in a general way from their previous experience. The same criteria were judged as in the specific system experiment.

Table VIII.2: Importance Weighting Techniques

Reference Source	Importance Weighting Technique
Dalkey (1969)	Delphi
Dean and Nishry (1965)	Paired comparison
Dee, et al. (1972)	Ranked pairwise comparison
Eckenrode (1965)	Ranking Rating Paired comparison (3 types) Successive comparison
Edwards (1976)	Multi-attribute utility measurement
Falk (1968)	Public preference
Finsterbusch (1977)	Consensal weights Formula weights Justified subjective weights Subjective weights Inferred subjective weights Ranking Equal weight Multiple methods
Gum, Roefs and Kimball (1976)	Metfessel general allocation test
O'Connor (1972)	Multi-attribute scaling
Ross (1976)	Paired comparison and checking
School of CEES and Oklahoma Biological Survey (1974)	Ranked pairwise comparison
Toussaint (1975)	Delphi
Voelker (1977)	Nominal group process

(3) A personnel selection problem, in which six judges who had extensive experience in personnel subsystem management judged the relative value of the following carefully defined qualifications for a command and control personnel subsystem manager: previous personnel subsystem experience, technical competence, and demonstrated capabilities for fiscal planning, work planning, and maintaining good client relations and good staff relations.

It is realized that these three experiments do not address aquifer restoration strategies; however, they can be used generically since they involve importance weighting of decision factors (criteria). The six importance weighting techniques which were compared for their reliability and efficiency in collecting the judgment data were (Eckenrode, 1965):

(1) Ranking: The judge (J) was asked to place a numerical rank next to each criterion, indicating by 1 that criterion most valuable in the situation, by 2, the next most valuable, etc.

(2) Rating: The criteria were presented next to a continuous scale marked off in units from 0 to 10 (see Figure VIII.1). J was asked to draw a line from each criterion to any appropriate point on the value scale. He was permitted to select points between numbers or to assign more than one criterion to a single position on the scale.

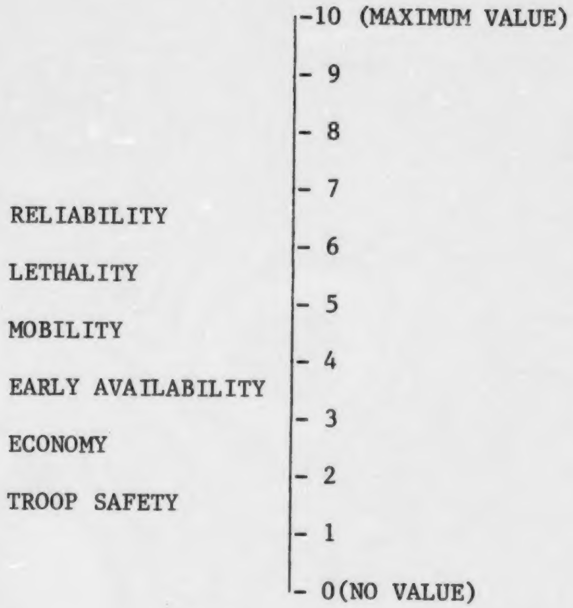
(3) Partial Paired Comparisons I: The criteria were presented on the ordinate and abscissa of a partial matrix (see Table VIII.3). J was asked to indicate in each block the number of the more valuable of the pair of criteria which were the coordinates of that block.

(4) Partial Paired Comparisons II: A list of criterion pairs was presented in the form illustrated below, and J was asked to circle the member of each pair which was more valuable for the system in question.

Troop safety -- Reliability

Each criterion was paired once with every other criterion.

(5) Complete Paired Comparisons: This method was the same as partial paired comparisons II, except that the list was doubled in length by requiring that each pair appear twice,


-10 (MAXIMUM VALUE)
- 9
- 8
- 7
RELIABILITY
- 6
LETHALITY
- 5
MOBILITY
- 4
EARLY AVAILABILITY
- 3
ECONOMY
- 2
TROOP SAFETY
- 1
- 0(NO VALUE)

Note: J draws a line from each criterion to the appropriate point on the scale.

Figure VIII.1: Rating Scale (Eckenrode, 1965).

Table VIII.3: Partial Paired Comparisons I (Eckenrode, 1965).

	2. TROOP SAFETY	3. MOBILITY	4. ECONOMY	5. RELIABILITY	6. LETHALITY
1. EARLY AVAILABILITY					
2. TROOP SAFETY					
3. MOBILITY					
4. ECONOMY					
5. RELIABILITY					

Note: J puts the number of the more valuable criterion of the pair being considered in each block. Example: 2 in the "early availability-troop safety" block means J judges the latter to be more important for the system in question.

once in the order A-B, the second time (elsewhere in the list) in the order B-A, in order to eliminate any position error.

(6) Successive Comparisons: In this method the list of criteria was presented to J who proceeded as follows:

(a) He ranked criteria in order of importance (as in the ranking method above).

(b) He tentatively assigned the value (V_1) 1.0 to the most important criterion, and other values (V_i) between 0 and 1 to the other criteria in order of importance.

(c) He decided whether the criterion with value 1.0 was more important than all other criteria combined.

If so, he increased V_1 so that V_1 was greater than the sum of all subsequent V's, i.e.,

$$V_1 > \Sigma_2^n V_i$$

If not, he adjusted V_1 (if necessary) so that V_1 was less than the sum of all subsequent V's, i.e.,

$$V_1 < \Sigma_2^n V_i$$

(d) He decided whether the second most important criterion with value V_2 was more important than all lower-valued criteria; he then proceeded as in c above with V_2.

(e) He continued until n - 1 criteria had been so evaluated.

All methods except successive comparison were used in all three experiments. The successive comparisons method was used only in the first experiment, in which the criteria were applied to a specific hardware system design. All three experiments were conducted in the same way. For each, a booklet was developed, the cover page of which contained instructions to the judge, including a definition of each criterion to be compared. Each succeeding page contained a form for recording his judgments by one of the methods. The order of the forms in the booklet was randomized and each judge was administered a booklet individually in a quiet office, under instructions to complete it rapidly but without making mistakes. The experimenter recorded the time required by the judge to complete each page of the booklet.

The consistency of importance weighting assignments among the six techniques was very high in all three experiments. This means that there is high reliability among the techniques in the importance weights produced; that is, each method produced essentially the same ordering of weights. It was also noted that each judge produced the same ordering of weights regardless of the method he used. This high within-judge reliability is to be expected when the set of items being judged is small as in the present experiments and judges behave transitively. This is the usual case in weighting multiple criteria, for sets of criteria to be weighted frequently consist of between three and a dozen items in practical situations. Taken together, this information indicates that the techniques are reliable approaches for recording judgments. Any of the six techniques could be used for importance weighting of decision factors associated with the selection of an aquifer restoration strategy. The individuals doing the weighting could be technical specialists or public officials, or both.

RANKING TECHNIQUES FOR IMPORTANCE WEIGHTING

Ranking techniques for importance weighting basically involve the rank ordering of decision factors in their relative order of importance. If there are "n" decision factors, rank ordering would involve assigning 1 to the most important factor, 2 to the second-most important factor, and so forth until "n" is assigned to the least important factor. It should be noted that the rank order numbers could be reversed; that is, "n" could be assigned to the most important factor, "n-1" to the second most important factor, and so forth until 1 is assigned to the least important factor. Two illustrations of ranking techniques will be briefly described herein: (1) a public preference approach (Falk, 1968); and (2) the use of the Nominal Group Process technique (Voelker, 1977). Both of these techniques could be used for importance weighting of decision factors associated with the selection of an aquifer restoration strategy for meeting a given need.

Public Preference Approach

Falk (1968) described the use of public participation in the assignment of relative importance weights to a series of factors. A pilot study was described which involved determining the relative importance of four tangible and five intangible factors, and identifying a means of applying these measures of importance in selecting the most acceptable one of three hypothetical roadway solutions. The approach requires the assumption that frequency of citizen preference for one factor over another is directly related to importance of that factor. This approach could be used in the selection of an aquifer restoration strategy for meeting a given need, and public participation techniques are described in Appendix E.

Nominal Group Process Technique

The Nominal Group Process technique (NGP), an interactive group technique, was developed in 1968. It was derived from social-psychological studies of decision conferences, management-science studies of aggregating group judgments, and social-work studies of problems surrounding citizen participation in program planning. The NGP has gained wide acceptance in health, social service, education, industry, and government organizations. For example, Voelker (1977) described the application of NGP to rank decision factors important in siting nuclear power plants. Siting decisions are routinely required for injection wells for treated ground water. The following four steps are involved in the use of NGP for importance weighting:

(1) Nominal (silent and independent) generation of ideas in writing by a panel of participants.

(2) Round-robin listing of ideas generated by participants on a flip chart in a serial discussion.

(3) Discussion of each recorded idea by the group for the purpose of clarification and evaluations.

(4) Independent voting on priority ideas, with group decision determined by mathematical rank-ordering.

RATING TECHNIQUES FOR IMPORTANCE WEIGHTING

Rating techniques for importance weighting basically involve the assignment of importance numbers to a series of decision factors, and possibly, although not always, their subsequent normalization via a mathematical procedure. An example of a rating scale approach is shown in Figure VIII.1 (Eckenrode, 1965). Four additional examples of rating techniques will be presented herein: (1) the use of a pre-defined importance scale (Linstone and Turoff, 1975); (2) the use of a group approach for the assignment of scales of importance (Rau, 1980); (3) the use of the multi-attribute utility measurement technique (Edwards, 1976); (4) and the use of a computerized version of a multi-attribute utility measurement technique (Rugg and Feldman, 1982). These four rating techniques could be used for importance weighting of decision factors associated with the selection of an aquifer restoration strategy for meeting a given need. It should be noted that the public preference approach (Falk, 1968) and the NGP technique (Voelker, 1977) described in the previous sub-section could also be used for rating the importance of decision factors.

Pre-defined Importance Scale

Decision factors can be assigned numerical values based on pre-defined importance scales. Table VIII.4 delineates five scales with definitions to be considered in the assignment of numerical values to decision factors (Linstone and Turoff, 1975). Usage of the pre-defined scales can aid in systematizing importance weight assignments.

Group Approach Using Scales of Importance

Rau (1980) suggested a group approach for importance weight assignments, with the approach following a procedure that will produce reliable results. Because these weights are essentially based on the judgmental values or attitudes of those surveyed, the selected procedure must be systematic and must be able to reduce all possible variation. The group of persons ultimately selected for the weighting should include a cross section of society such as individuals from governmental agencies, politicians and decision makers, experts in the field of hydrogeology and environmental evaluation, representatives from special interest groups, and members of the general public. Groups of individuals representing this cross section must be sampled a number of times to obtain consistent estimates of the weights.

Table VIII.4: Importance Scale (Linstone and Turoff, 1975).

Scale Reference	Definitions
1. Very Important	A most relevant point First order priority Has direct bearing on major issues Must be resolved, dealt with or treated
2. Important	Is relevant to the issue Second order priority Significant impact but not until other items are treated Does not have to be fully resolved
3. Moderately Important	May be relevant to the issue Third order priority May have impact May be a determining factor to major issue
4. Unimportant	Insignificantly relevant Low priority Has little impact Not a determining factor to major issue
5. Most Unimportant	No priority No relevance No measurable effect Should be dropped as an item to consider

The procedure suggested by Rau (1980) for determining the relative importance of each decision factor (environmental impact area in this example) consists of ranking and pair-wise comparisons. Each individual is required to rank the impact areas and to compare in pair-wise fashion the degree of importance of highest rank with the one immediately following. If this procedure is followed in a systematic way, a weight will be developed for each area. The procedure is repeated a number of times for different groups in order to get the desired cross-sectional population representation and the reliability needed for an importance weighting. The basic steps for determining the importance weightings are as follows (Rau, 1980):

(1) Step 1: Select a group of individuals for evaluation and explain to them in detail the weighting concept and the use of rankings and weightings.

(2) Step 2: Prepare a table with columns corresponding to the range of values which can be assigned as a "score of importance" to each impact area -- for example, if five values are possible, there would be five columns. The rows in the table would correspond to the impact areas being ranked as to importance. Table VIII.5 contains an illustration of five columns for importance weighting (Rau, 1980).

(3) Step 3: Give a copy of the table developed in Step 2 to each individual evaluator and repeat Steps 4-9 until no further changes in the table entries are desired.

(4) Step 4: Ask each individual to place an "X", or other signifying mark, in each column for each impact area. Thus, a value of importance is assigned to each impact area.

(5) Step 5: Ask all individuals to compare the marked columns on a pair-wise basis to insure that the impact areas are ordered on the proper relative basis in their opinion. If not, they should reassign their scores so as to have the desired relative ordering of impact areas. (For example, on a scale from 1 to 10, if a value of 10 has been assigned to impact area A and it appears that A is twice as important as B, impact area B should be assigned a value of 5.)

Table VIII.5: Example of the Development of Impact Area Importance Weightings (Rau, 1980)

Impact area	Low importance ↓ 1	2	Average importance ↓ 3	4	High importance ↓ 5	Total	Weighting
Park requirements		X				2	2/43
School age students generated			X			3	3/43
Trips generated		X				2	2/43
Police protection				X		4	4/43
Fire protection				X		4	4/43
Public service costs					X	5	5/43
Total revenues					X	5	5/43
Employment (long-term jobs)				X		4	4/43
Electricity consumption			X			3	3/43
Natural gas consumption			X			3	3/43
Solid waste generated		X				2	2/43
Sewage discharge			X			3	3/43
Water consumption			X			3	3/43
						43	1.0

(6) Step 6: Ask each individual to add the value (or importance score) selected for each of the impact areas to obtain a total.

(7) Step 7: The individual should then divide the value selected for each impact area by the total obtained in Step 6 to determine the desired weighting for each area.

(8) Step 8: Collect the tables from each individual evaluator and average the weightings determined for each impact area to obtain a "group or composite average".

(9) Step 9: Present the averages obtained to the individual evaluators and ask them to compare the group weightings with those derived by each of them individually in Step 7.

(10) Step 10: If any one or more individuals desires to change the assignment of scores based on what the group decided, go to Step 4 and repeat the entire process. If none desire to change their scores, stop the experiment, because the impact area relative weightings of importance will have been derived.

As referred to earlier, Table VIII.5 contains an example of importance weight assignments to 13 impact areas of interest based on 5 possible importance scores (Rau, 1980). By adding the scores corresponding to each "X", a total of 43 points is obtained. Dividing each score by 43, the relative importance weightings given by the last column in Table VIII.5 are determined.

Multi-Attribute Utility Measurement Technique

Edwards (1976) described the multi-attribute utility measurement (MAUM) technique for use in decision-making involving different publics. The MAUM technique can be used to spell out explicitly what the values of each participant (decision-maker, expert, pressure group, government, etc.) are, show how much they differ, and in the process can frequently reduce the extent of such differences. The basic assumption is that the values of the participants are reflected in the importance weights assigned to individual factors. It should also be noted that the usage of the MAUM technique can be by an individual, a small group of persons, or multiple publics. The 10 basic steps in the MAUM technique are (Edwards, 1976):

(1) Step 1: Identify the person or organization whose utilities are to be maximized. If, as is often the case, several organizations have stakes and voices in the decision, they must all be identified (Utilities refer to general goals or objectives in the terminology used herein).

(2) Step 2: Identify the issue or issues to which the utilities needed are relevant. (Issues refer to needs being addressed.)

(3) Step 3: Identify the entities to be evaluated. Formally, they are outcomes of possible actions. But in a sense, the distinction between an outcome and the opportunity for further actions is usually fictitious. (Entities refer to alternatives in the terminology used herein; outcomes would reflect the evaluation of each entity relative to the decision factors.)

(4) Step 4: Identify the relevant dimensions of value for evaluation of the entities. As has often been noted, goals ordinarily come in hierarchies. But it is often practical and useful to ignore their hierarchical structure, and instead to specify a simple list of goals that seem important for the purpose at hand. It is important not to be too expansive at this stage. The number of relevant dimensions of value should be modest, for reasons that will be apparent shortly. (It should be noted that dimensions of value refer to the decision factors for evaluation of the alternatives.)

(5) Step 5: Rank the dimensions in order of importance. This ranking job, like Step 4, can be performed either by an individual or by representatives of conflicting values acting separately or by those representatives acting as a group.

(6) Step 6: Rate dimensions in importance, preserving ratios. To do this, start by assigning the least important dimension an importance of 10. Now consider the next-least-important dimension. How much more important (if at all) is it than the least important? Assign it a number that reflects that ratio. Continue up the list, checking each set of implied ratios as each new judgment is made. Thus, if a dimension is assigned a weight of 20, while another is assigned a weight of 80, it means that the 20 dimension is 1/4 as important as the 80 dimension, and so on. By the time you get to the most important dimensions, there will be many checks to perform;

typically, respondents will want to review previous judgments to make them consistent with present ones.

(7) Step 7: Sum the importance weights, divide each by the sum, and multiply by 100. This is a purely computational step which converts importance weights into numbers that, mathematically, are rather like probabilities. The choice of a 1-to-100 scale is, of course, completely arbitrary.

(8) Step 8: Measure the location of each entity being evaluated on each dimension. The word "measure" is used rather loosely here. There are three classes of dimensions: purely subjective, partly subjective, and purely objective. The purely subjective dimensions are perhaps the easiest; you simply get an appropriate expert to estimate the position of the entity on that dimension on a 0-to-100 scale, where 0 is defined as the minimum plausible value and 100 is defined as the maximum plausible value. Note 'minimum and maximum plausible" rather than "minimum and maximum possible". The minimum plausible value often is not total absence of the dimension. A partly subjective dimension is one in which the units of measurement are objective, but the locations of the entities must be subjectively estimated. A purely objective dimension is one that can be measured non-judgmentally, in objective units, before the decision. For partly or purely objective dimensions, it is necessary to have the estimators provide not only values for each entity to be evaluated, but also minimum and maximum plausible values, in the natural units of each dimension.

(9) Step 9: Calculate utilities for entities. The equation is:

$$U_i = \sum_j w_j u_{ij}$$

where:

U_i = aggregate utility for ith entity (overall evaluation score, or index, for the ith alternative)

i = number of entities (number of alternatives)

w_j = normalized importance weight of the jth dimension of value (importance weight for jth decision factor); the w_j values are the output from Step 7.

j = number of dimensions of value (number of decision factors).

u_{ij} = scaled position of the ith entity on the jth dimension (scaled position of ith alternative on jth decision factor); the u_{ij} measures are the output from Step 8.

(10) Step 10: Decide. If a single act is to be chosen, the rule is simple: maximize u_i. If a subset of i is to be chosen, then the subset for which $\sum_i u_i$ is maximum at best.

Computerized Version of MAUM Technique

A simple computer program, called DECIDE, for use in importance weighting and decision-making is available for the TRS-80 computer system (Rugg and Feldman, 1982). The program can aid in decision-making when the decision involves the selection of one alternative from several choices. The following information describes how the program can be used.

(1) The first thing the program does is ask you to categorize the decision at hand into one of three categories: (1) choosing an item (or thing), (2) choosing a course of action, or (3) making a yes or no decision. You simply press 1, 2, or 3 followed by the ENTER key to indicate which type of decision is facing you. If you are choosing an item, you will be asked what type of item it is. To illustrate the mechanisms of the computer program, Table VIII.6 contains a sample run (Rugg and Feldman, 1982). This illustration could easily be adapted to decisions related to the selection of an aquifer restoration strategy for meeting a given need.

(2) If the decision is either of the first two types, you must next enter a list of all the possibilities under consideration. A question mark will prompt you for each one. When the list is complete, type "END" in response to the last question mark. You must, of course, enter at least two possibilities. After the list is finished, it will be re-displayed so that you can verify that it is correct. If not, you must re-enter it.

(3) Now you must think of the different factors that are important to you in making your decision. Each factor is to be entered one at a time with the word "END" used to terminate the list. When complete, the list will be re-displayed. You must now decide which single factor is the most important and input its number. (You can enter 0 if you wish to change the list of factors.)

Table VIII.6: Illustration of the Use of DECIDE (Rugg and Feldman, 1982)

```
I CAN HELP YOU MAKE A DECISION.  ALL I NEED TO DO IS ASK SOME QUESTIONS
AND THEN ANALYZE YOUR RESPONSES.

- - - - - - - - - - -

WHICH OF THESE BEST DESCRIBES THE DECISION FACING YOU?

        1)   CHOOSING AN ITEM FROM VARIOUS ALTERNATIVES.
        2)   CHOOSING A COURSE OF ACTION FROM VARIOUS ALTERNATIVES.
        3)   DECIDING "YES" OR "NO".

WHICH ONE (1, 2, OR 3)?  1

WHAT TYPE OF ITEM IS IT

?    VACATION

I NEED TO HAVE A LIST OF EACH VACATION UNDER CONSIDERATION.

INPUT THEM ONE AT A TIME IN RESPONSE TO EACH QUESTION MARK.

TYPE THE WORD "END" TO INDICATE THAT THE WHOLE LIST HAS BEEN ENTERED.

?    CAMPING
?    SAFARI
?    TRIP TO D.C.
?    END

OK.  HERE'S YOUR LIST:

        1)   CAMPING
        2)   SAFARI
        3)   TRIP TO D.C.

IS THE LIST CORRECT (Y OR N)?  Y

NOW, THINK OF THE FACTORS THAT ARE IMPORTANT IN CHOOSING THE BEST
VACATION.

INPUT THEM ONE AT A TIME IN RESPONSE TO EACH QUESTION MARK.

TYPE THE WORD "END" TO TERMINATE THE LIST.

?    RELAXATION
?    AFFORDABILITY
?    CHANGE OF PACE
?    END
```

Table VIII.6: (continued)

```
HERE'S YOUR LIST OF FACTORS:

     1)   RELAXATION
     2)   AFFORDABILITY
     3)   CHANGE OF PACE

DECIDE WHICH FACTOR ON THE LIST IS THE MOST IMPORTANT AND INPUT ITS
NUMBER.  (TYPE 0 IF THE LIST NEEDS CHANGING.)

?   2

NOW LET'S SUPPOSE WE HAVE A SCALE OF IMPORTANCE RANGING FROM 0-10.
WE'LL GIVE AFFORDABILITY A VALUE OF 10 SINCE AFFORDABILITY WAS RATED THE
MOST IMPORTANT.

ON THIS SCALE, WHAT VALUE OF IMPORTANCE WOULD THE OTHER FACTORS HAVE?

RELAXATION

?   5.5

CHANGE OF PACE

?   9

EACH VACATION MUST NOW BE COMPARED WITH RESPECT TO EACH IMPORTANCE
FACTOR.

WE'LL CONSIDER EACH FACTOR SEPARATELY AND THEN RATE EACH VACATION IN
TERMS OF THAT FACTOR ONLY.

*** (HIT ANY KEY TO CONTINUE)

(A key is pressed)

LET'S GIVE CAMPING A VALUE OF 10 ON EVERY SCALE.

EVERY OTHER VACATION WILL BE ASSIGNED A VALUE HIGHER OR LOWER THAN 10.
THIS VALUE DEPENDS ON HOW MUCH YOU THINK IT IS BETTER OR WORSE THAN
CAMPING.

- - - - - - - - - -

CONSIDERING ONLY RELAXATION AND ASSIGNING 10 TO CAMPING,

WHAT VALUE WOULD YOU ASSIGN TO
```

Table VIII.6: (continued)

```
SAFARI? 3

TRIP TO D.C.? 9

- - - - - - - - - - -

CONSIDERING ONLY AFFORDABILITY AND ASSIGNING 10 TO CAMPING,

WHAT VALUE WOULD YOU ASSIGN TO

SAFARI? 1

TRIP TO D.C.? 8

- - - - - - - - - - -

CONSIDERING ONLY CHANGE OF PACE AND ASSIGNING 10 TO CAMPING,

WHAT VALUE WOULD YOU ASSIGN TO

SAFARI? 60

TRIP TO D.C.? 25


TRIP TO D.C. IS BEST BUT IT'S VERY CLOSE.

HERE'S THE FINAL LIST IN ORDER.  TRIP DO D.C. HAS BEEN GIVEN A VALUE OF
100 AND THE OTHERS RATED ACCORDINGLY.

HIT ANY KEY TO SEE THE LIST.

(A key is pressed)

100       TRIP TO D.C.

 98.7     CAMPING

 78.8     SAFARI

OK
```

(4) The program now asks you to rate the importance of each of the other factors relative to the most important one. This is done by first assigning a value of 10 to the main factor. Then you must assign a value from 0-10 to each of the other factors. These numbers reflect your assessment of each factor's relative importance as compared to the main one. A value of 10 means it is just as important; lesser values indicate how much less importance you place on it.

(5) Now you must rate the decision possibilities (alternatives) with respect to each of the importance factors. Each importance factor will be treated separately. Considering only that importance factor, you must rate each decision possibility. The program first assigns a value of 10 to one of the decision possibilities. Then you must assign a relative number (lower, higher, or equal to 10) to each of the other decision possibilities.

(6) Armed with all this information, the program will now determine which choice is best. The various possibilities are listed in order of ranking. Alongside each one is a relative rating with the best choice being normalized to a value of 100.

The DECIDE program listing is in Table VIII.7; the program can currently accept up to ten alternatives and ten decision factors. If more alternatives are to be evaluated, or if more decision factors are involved, the value of MD in line 160 in the program listing should be increased. The main routines in the DECIDE computer program are as follows (Rugg and Feldman, 1982):

150- 190	Initializes and dimensions variables.
200- 360	Determines category of decision.
400- 490	Gets or sets T$.
500- 810	Gets list of possible alternatives from user.
900-1220	Gets list of importance factors from user.
1300-1490	User rates each importance factor.
1500-1900	User rates the decision alternatives with respect to each importance factor.
2000-2110	Evaluates the various alternatives.
2200-2270	Sorts alternatives into their relative ranking.
2300-3000	Displays results.
5000-5020	Subroutine to clear screen and display header.
5200	Time wasting subroutine.

Table VIII.7: Program Listing for DECIDE (Rugg and Feldman, 1982)

```
100     REM:  DECIDE - 16K
110     REM:  (C) 1981, PHIL FELDMAN AND TOM RUGG
150     CLEAR 500
160     MD=10
170     DIM L$(MD),F$(MD),V(MD)
180     DIM C(MD,MD),D(MD),Z(MD)
190     E$="END"
200     GOSUB 5000
210     PRINT" I CAN HELP YOU MAKE A"
220     PRINT"DECISION.  ALL I NEED TO DO IS"
230     PRINT"ASK SOME QUESTIONS AND THEN"
240     PRINT"ANALYZE YOUR RESPONSES."
250     FOR J=1 TO 30:PRINT"-";:NEXT
260     PRINT
270     PRINT"WHICH OF THESE BEST DESCRIBES"
280     PRINT"THE DECISION FACING YOU?"
290     PRINT" 1) CHOOSING AN ITEM FROM"
300     PRINT" VARIOUS ALTERNATIVES."
310     PRINT" 2) CHOOSING A COURSE OF ACTION"
320     PRINT" FROM VARIOUS ALTERNATIVES."
330     PRINT" 3) DECIDING 'YES' OR 'NO'."
340     PRINT
350     INPUT"WHICH ONE (1,2,OR 3)";T
360     IF T<1 OR T>3 THEN 200
400     GOSUB 5000
410     ON T GOTO 420,440,460
420     PRINT"WHAT TYPE OF ITEM IS IT"
430     INPUT T$:GOTO 500

440     T$="COURSE OF ACTION"
450     GOTO 500
460     T$="'YES' OR 'NO'":NI=2
470     L$(1)="DECIDING YES"
480     L$(2)="DECIDING NO"
490     GOTO 900
500     GOSUB 5000:NI=0
510     PRINT" I NEED TO HAVE A LIST OF EACH"
520     PRINT T$;" UNDER"
530     PRINT"CONSIDERATION.":PRINT
540     PRINT" INPUT THEM ONE AT A TIME IN"
550     PRINT"RESPONSE TO EACH QUESTION MARK."
560     PRINT
570     PRINT" TYPE THE WORD '";E$;"' TO"
580     PRINT"INDICATE THAT THE WHOLE LIST"
590     PRINT"HAS BEEN ENTERED.":PRINT
```

Table VIII.7: (continued)

```
600     IF NI MD THEN 620
610     PRINT"-LIST FULL-":GOTO 650
620     NI=NI+1:INPUT L$(NI)
630     IF L$(NI)  E$ THEN 600
640     NI=NI-1
650     IF NI =2 THEN 700
660     PRINT
670     PRINT"YOU NEED AT LEAST 2 CHOICES!"
680     PRINT:PRINT"TRY AGAIN"
690     GOSUB 5200:GOTO 500
700     GOSUB 5000
710     PRINT"OK. HERE'S YOUR LIST:"
720     PRINT:FOR J=1 TO NI
730     PRINT J;CHR$(8);") ";L$(J)
740     NEXT:PRINT
750     FOR J=1 TO 9:R$=INKEY$:NEXT
760     INPUT"IS THE LIST CORRECT (Y OR N)";R$
770     IF R$="Y" THEN 900
780     IF R$<>"N" GOTO 700
790     PRINT
800     PRINT"THE LIST MUST BE RE-ENTERED"
810     GOSUB 5200:GOTO 500
900     GOSUB 5000:R$=INKEY$
910     PRINT" NOW, THINK OF THE FACTORS THAT"
920     IF T<3 THEN PRINT"ARE IMPORTANT IN CHOOSING THE"
930     IF T<3 THEN PRINT"BEST ";T$;"."
940     IF T=3 THEN PRINT"ARE IMPORTANT TO YOU IN"
950     IF T=3 THEN PRINT"DECIDING ";T$;"."
960     PRINT:PRINT" INPUT THEM ONE AT A TIME IN"
970     PRINT"RESPONSE TO EACH QUESTION MARK."
980     PRINT:PRINT" TYPE THE WORD '";E$;"' TO"
990     PRINT"TERMINATE THE LIST."
1000    PRINT:NF=0
1010    IF NF>=MD THEN PRINT"-- LIST FULL --":PRINT
1020    IF NF>=MD THEN GOTO 1060
1030    NF=NF+1:INPUT F$(NF)
1040    IF F$(NF)<>E$ THEN 1010
1050    NF=NF-1:PRINT
1060    IF NF<1 THEN PRINT"YOU NEED AT LEAST 1 - REDO IT !"
1070    IF NF<1 THEN GOSUB 5200
1080    IF NF<1 THEN 900
1100    GOSUB 5000
1110    PRINT"HERE'S YOUR LIST OF FACTORS:"
1130    FOR J=1 TO NF
1140    PRINT J;CHR$(B);") ";F$(J)
```

Table VIII.7: (continued)

```
1150   NEXT
1160   PRINT"DECIDE WHICH FACTOR ON THE"
1170   PRINT"LIST IS THE MOST IMPORTANT AND"
1180   PRINT"INPUT ITS NUMBER.  (TYPE 0 IF"
1190   PRINT"THE LIST NEEDS CHANGING.)"
1200   INPUT A:A=INT(A)
1210   IF A=0 THEN 900
1220   IF A>NF OR A<0 THEN 1100
1300   GOSUB 5000
1310   IF NF=1 THEN 1500
1320   PRINT" NOW LET'S SUPPOSE WE HAVE A"
1330   PRINT"SCALE OF IMPORTANCE RANGING"
1340   PRINT"FROM 0-10.  WE'LL GIVE"
1350   PRINT F$(A);" A VALUE OF"
1360   PRINT"10 SINCE ";F$(A)
1370   PRINT"WAS RATED THE MOST IMPORTANT."
1380   PRINT:PRINT" ON THIS SCALE, WHAT VALUE OF"
1390   PRINT"IMPORTANCE WOULD THE OTHER"
1400   PRINT"FACTORS HAVE?"
1410   FOR J=1 TO NF
1420   IF J=A THEN 1490
1430   PRINT:PRINT F$(J)
1440   INPUT V(J)

1450   IF V(J)<0 THEN 1480
1460   IF V(J)>10 THEN 1480
1470   GOTO 1490
1480   PRINT" IMPOSSIBLE VALUE - TRY AGAIN":GOTO 1430
1490   NEXT
1500   V(A)=10:Q=0:FOR J=1 TO NF
1510   Q=Q+V(J):NEXT:FOR J=1 TO NF
1520   V(J)=V(J)/Q:NEXT:GOSUB 5000
1530   IF T<>3 THEN PRINT" EACH ";T$;" MUST NOW"
1540   IF T=3 THEN PRINT" DECIDING 'YES' OR DECIDING"
1550   IF T=3 THEN PRINT"'NO' MUST NOW"
1560   PRINT"BE COMPARED WITH RESPECT TO"
1570   PRINT"EACH IMPORTANCE FACTOR."
1580   PRINT"WE'LL CONSIDER EACH FACTOR"
1590   PRINT"SEPARATELY AND THEN RATE"
1600   IF T<>3 THEN PRINT"EACH ";T$;" IN TERMS"
1610   IF T=3 THEN PRINT"DECIDING 'YES' OR DECIDING"
1620   IF T=3 THEN PRINT"'NO' IN TERMS"
1630   PRINT"OF THAT FACTOR ONLY."
1634   PRINT:PRINT"xxx (HIT ANY KEY TO CONTINUE)"
1638   R$=INKEY$:IF R$="" THEN1638
```

Table VIII.7: (continued)

```
1640    PRINT:PRINT" LET'S GIVE ";L$(1)
1650    PRINT"A VALUE OF 10 ON EVERY SCALE."
1660    IF T<>3 THEN PRINT" EVERY OTHER ";T$
1670    IF T=3 THEN PRINT" THEN DECIDING 'NO'"
1680    PRINT"WILL BE ASSIGNED A VALUE HIGHER"
1690    PRINT"OR LOWER THAN 10.  THIS VALUE"
1700    PRINT"DEPENDS ON HOW MUCH YOU THINK"
1710    PRINT"IT IS BETTER OR WORSE THAN"
1720    PRINT L$(1);"."
1800    FOR J=1 TO NF
1810    PRINT" ---------------"
1820    PRINT" CONSIDERING ONLY ";F$(J)
1830    PRINT"AND ASSIGNING 10 TO"
1835    PRINT L$(1);","
1840    PRINT"WHAT VALUE WOULD YOU ASSIGN TO"
1850    FOR K=2 TO NI
1860    PRINT L$(K);:INPUT C(K,J)
1870    IF C(K,J)>=0 THEN 1900
1880    PRINT" -- NEGATIVE VALUES ILLEGAL --"
1890    GOTO 1860
1900    NEXT:PRINT:C(1,J)=10:NEXT
2000    FOR J=1 TO NF:Q=0
2010    FOR K=1 TO NI
2020    Q=Q+C(K,J):NEXT
2030    FOR K=1 TO NI
2040    C(K,J)=C(K,J)/Q:NEXT:NEXT
2050    FOR K=1 TO NI:D(K)=0
2060    FOR J=1 TO NF
2070    D(K)=D(K)+C(K,J)*V(J):NEXT
2080    NEXT:MX=0:FOR K=1 TO NI
2090    IF D(K)>MX THEN MX=D(K)
2100    NEXT:FOR K=1 TO NI
2110    D(K)=D(K)*100/MX:NEXT
2200    FOR K=1 TO NI:Z(K)=K:NEXT
2210    NM=NI-1:FOR K=1 TO NI
2220    FOR J=1 TO NM:N1=Z(J)
2230    N2=Z(J+1)
2240    IF D(N1)>D(N2) THEN 2260
2250    Z(J+1)=N1:Z(J)=N2
2260    NEXT:NEXT:J1=Z(1):J2=Z(2)
2270    DF=D(J1)-D(J2):GOSUB 5000
2300    PRINT L$(J1);" IS BEST"
2310    IF DF<5 THEN PRINT"BUT IT'S VERY CLOSE."
2320    IF DF<5 THEN 2380
2330    IF DF<10 THEN PRINT"BUT IT'S FAIRLY CLOSE."
```

Table VIII.7: (continued)

```
2340   IF DF<10 THEN 2380
2350   IF DF<20 THEN PRINT"BY A FAIR AMOUNT."
2360   IF DF<20 THEN 2380
2370   PRINT"QUITE DECISIVELY."
2380   PRINT" HERE'S THE FINAL LIST IN"
2390   PRINT"ORDER. ";L$(J1)
2400   PRINT"HAS BEEN GIVEN A VALUE OF 100"
2410   PRINT"AND THE OTHERS RATED"
2420   PRINT"ACCORDINGLY."
2430   PRINT
2440   PRINT" HIT ANY KEY TO SEE THE LIST."
2450   R$=INKEY$
2460   IF R$="" THEN 2450
2470   PRINT
2400   FOR J=1 TO NI:Q=Z(J)

2490   PRINT D(Q),L$(Q):NEXT
3000   END
5000   FOR J=1 TO 500:NEXT
5010   CLS:PRINT@12,"DECIDE"
5020   PRINT:RETURN
5200   FOR J=1 TO 1500:NEXT:RETURN
```

Definitions for the main variables in the DECIDE computer program are as follows (Rugg and Feldman, 1982):

MD	Maximum number of decision alternatives.
NI	Number of decision alternatives.
NM	NI-1.
L$	String array of the decision alternatives.
NF	Number of importance factors.
F$	String array of the importance factors.
V	Array of the relative values of each importance factor.
A	Index number of most important factor.
C	Array of relative values of each alternative with respect to each importance factor.
T	Decision category (1=item, 2=course of action, 3=yes or no).
T$	String name of decision category.
E$	String to signal the end of an input data list.
J,K	Loop indices.
R$	User reply string.
Q,N1,N2	Work variables.
D	Array of each alternative's value.
MX	Maximum value of all alternatives.
DF	Rating difference between best two alternatives.
Z	Array of the relative rankings of each alternative.

PAIRED COMPARISON TECHNIQUES FOR IMPORTANCE WEIGHTING

Paired comparison techniques for importance weighting basically involve a series of comparisons between decision factors, and a systematic tabulation of the numerical results of the comparisons. These types of techniques have been extensively used in decision-making efforts, including numerous examples related to environmental improvement projects. Presented herein will be two examples of an unranked paired comparison technique (Dean and Nishry, 1965; Canter, 1983; Ross, 1976; and Hyman, Moreau and Stiftel, 1982); and two examples of a ranked pairwise comparison technique (Dee, et al., 1972; and School of Civil Engineering and Environmental Science and Oklahoma Biological Survey, 1974). Three examples of unranked paired comparison techniques were discussed earlier in relation to a systematic comparison of structured importance weighting techniques (Eckenrode, 1965). Both unranked and ranked pairwise comparison techniques can be used for weighting decision factors associated with the selection of an aquifer restoration strategy for meeting a given need.

Unranked Paired Comparison Techniques

One of the most useful techniques for importance weighting of a series of decision factors is the paired comparison technique developed by Dean and Nishry (1965). This technique, which can be used by an individual or group, involves the comparison of each decision factor to each other decision factor in a systematic manner. Suppose that there are four basic decision factors known as F1 through F4 (F1 could be health risks, F2 could be economic efficiency, F3 could be social concern, and F4 could be environmental impacts). The weighting technique consists of considering each factor relative to every other factor and assigning to the one of the pair considered to be the most important a value of 1, and to the lesser important of the pair a value of 0. The use of this paired comparison technique is shown in Table VIII.8. It should be noted that the assignment of 0 to a member of a pair does not denote zero importance; it simply mean that in the pair considered it is of lesser importance.

A dummy factor, called F5, is also included in Table VIII.8. The dummy factor is included so as to preclude the net assignment of a value of 0 to any of the basic factors (F1 through F4) in the process of each paired comparison. The dummy factor is defined as the least important in each paired comparison within which it is included. If two factors

Table VIII.8: Use of Paired-Comparison Technique for Importance Weight Assignments

Factor	Assignment of Weights										Sum	FIC
F1	1	1	1	1							4	0.40
F2	0				1	0	1				2	0.20
F3		0			0			0	1		1	0.10
F4			0			1		1		1	3	0.30
F5 (dummy)				0			0		0	0	0	0
											10	1.00

are considered to be of equal importance, then a value of 0.5 is assigned to each factor within the pair (Canter, 1983).

Following the assignment of relative importance to each factor relative to each other factor, with this process only being completed following several iterations to be sure that each factor is being considered in a consistent manner with each other factor, the rationale for each decision should be documented. It cannot be over-stressed that the most important aspect of using this technique is the careful delineation of the rationale basic to each 1 and 0 assignment. Following this documentation then the individual weight assignments are summed, with the factor importance coefficient (FIC) being equal to the sum value for an individual factor divided by the sum for all of the factors. The total of the sum column should equal to (N)(N-1)/2 where N is equal to the number of factors included in the assignment of weights. In the example in Table VIII.8, five factors were included, hence the sum column total should be equal to 10. The total of the FIC column in Table VIII.8 should equal to 1.00.

The FIC column in Table VIII.8 indicates that F1 is more important followed by F4, F2, and F3. Whether or not the actual FIC fractions are used in a trade-off analysis, this paired-comparison approach has enabled the rank ordering of the four decision factors from most important to least important. In addition, importance weighting of sub-factors can also be done by the same method. For example, in Table VIII.1 environmental impacts also includes biophysical, cultural, and socio-economic impacts.

The paired-comparison technique based on Dean and Nishry (1965) has been used in a number of environmentally-related studies. Examples include selection of a sanitary landfill site (Morrison, 1974), selection of a wastewater treatment system (Canter, 1976), presentation of an environmental impact methodology for water resources projects (Solomon, et al., 1977), and evaluation of the environmental impacts of a wastewater treatment system (Canter and Reid, 1977).

Ross (1976) described a method to check for the consistency of importance weight assignments made via the paired comparison technique. The paired comparison technique and consistency procedure proposed by Ross (1976) is as follows:

(1) When using this technique, an individual who has been requested to assess a number (N) of decision factors is presented with every possible combination of these factors, and asked to make judgments as to which of each pair is more important. His decisions are recorded in a paired-comparison matrix as shown in Table VIII.9. An entry (C_{ij}) of "1" in this matrix denotes that the row decision factor i (row stimulus) was judged as being better, or more desirable, than the column stimulus j. Once all possible pairs have been compared, and the decisions recorded in the matrix, the ranking of stimuli can be readily ascertained by summing the rows of the matrix. The stimuli are ranked in order of these row sums.

(2) For the information in Table VIII.9, the resultant ordering of the stimuli is 5, 6, 1, 3, 2, and 4. When the paired-comparison matrix is permuted according to the ranking derived, a characteristic pattern appears in which the upper right portion of the matrix is observed to be composed of 1's, and the lower left portion of 0's (see Table VIII.10).

In the foregoing example, the individual making the comparisons, hereafter termed the judge, has been perfectly consistent in his judgments. It reveals that he has a clear idea of the stimuli, and that he has a good decision rule to follow while making the individual paired comparisons. Such is often not the case. Inconsistent judgments are

Table VIII.9: Example Comparison Matrix (Ross, 1976)

Stimulus*	1	2	3	4	5	6	Row Sum
1	-	1	1	1	0	0	3
2	0	-	0	1	0	0	1
3	0	1	-	1	0	0	2
4	0	0	0	-	0	0	0
5	1	1	1	1	-	1	5
6	1	1	1	1	0	-	4

*Decision factors

Table VIII.10: Permuted Example Comparison Matrix (Ross, 1976).

Stimulus	5	6	1	3	2	4	Row Sum
5	-	1	1	1	1	1	5
6	0	-	1	1	1	1	4
1	0	0	-	1	1	1	3
3	0	0	0	-	1	1	2
2	0	0	0	0	-	1	1
4	0	0	0	0	0	-	0

revealed by the presence of 1's below the diagonal in the permuted matrix. In Table VIII.11, for example, the preference of the judge for 4 over 5 is revealed. It is clearly a case of inconsistent judgment and may indicate an unclear understanding of the stimuli, or a confused or poor decision rule. It might also indicate that one attribute of stimulus 4 was so far superior to that of stimulus 5 that it became the sole determinant of the choice made in that particular comparison. The paired-comparison technique permits and identifies inconsistencies that would be lost in more traditional ranking approaches (Ross, 1976).

Hyman, Moreau and Stiftel (1982) have indicated that substantial advances were made during the first decade of environmental impact studies relative to eliciting and displaying expert judgments about the relative importance of effects. In order to further these advances they developed a new environmental assessment method known as SAGE. SAGE stands for Social-judgment capturing -- Adaptive -- Goals-achievement -- Environmental assessment because it builds on the best characteristics of several existing methods. The concepts of SAGE can be used in the selection of an aquifer restoration strategy from a set of alternatives.

SAGE must be understood within an overall framework for assessing the relative social worth of alternative projects or policies. The general framework is that of the rational planning model, which is shown in Figure VIII.2 as consisting of two phases: (1) a design phase; and (2) an analytical phase. The design phase includes the tasks of (1) identifying objectives, (2) establishing planning guides and criteria, and (3) searching for and synthesizing alternative designs. The analytical phase comprises four tasks: (1) identifying and predicting

Table VIII.11: Permuted Example Comparison Matrix (Inconsistent) (Ross, 1976).

Stimulus	5	6	1	3	2	4	Row Sum
5	-	1	1	1	1	0	4
6	0	-	1	1	1	1	4
1	0	0	-	1	1	1	3
3	0	0	0	-	1	1	2
2	0	0	0	0	-	1	1
4	1	0	0	0	0	-	1

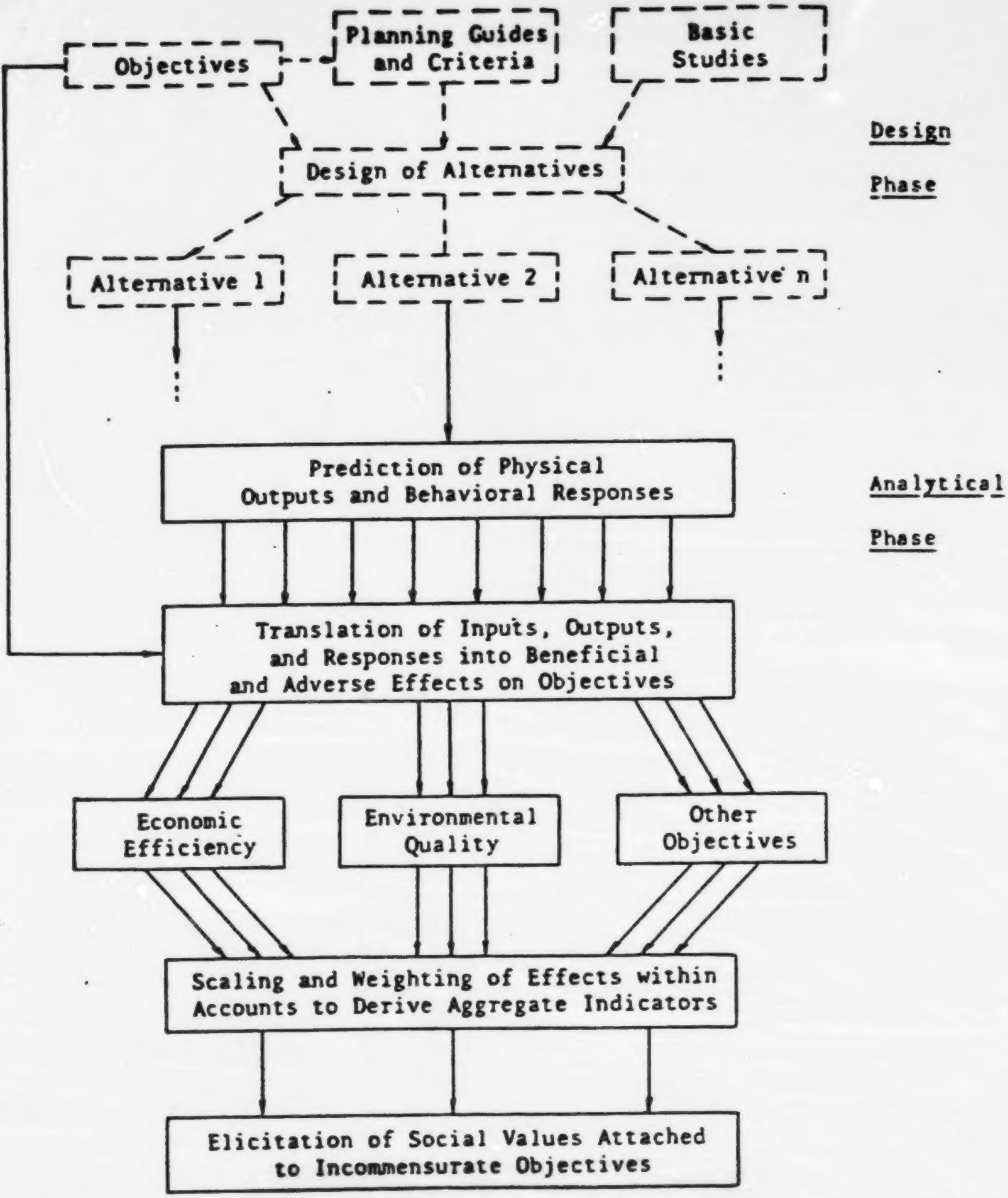

Objectives
Planning Guides and Criteria
Basic Studies
Design of Alternatives
Alternative 1
Alternative 2
Alternative n
Prediction of Physical Outputs and Behavioral Responses
Translation of Inputs, Outputs, and Responses into Beneficial and Adverse Effects on Objectives
Economic Efficiency
Environmental Quality
Other Objectives
Scaling and Weighting of Effects within Accounts to Derive Aggregate Indicators
Elicitation of Social Values Attached to Incommensurate Objectives
Design Phase
Analytical Phase

Figure VIII.2: Design and Analytical Phases of the SAGE Method (Hyman, Moreau, and Stiffel, 1982).

operational measures of the physical, chemical, and biological attributes of each alternative; (2) scaling or translating those consequences into accounts of beneficial and adverse effects on each objective including behavioral consequences; (3) eliciting relative value weights that affected individuals or groups attach to the contributions to each objective when they rank alternatives preferentially; and (4) presenting the results in a form that is useful to decision makers. This division of the rational planning model is convenient because SAGE is concerned primarily with the analytical phase (Hyman, Moreau and Stiftel, 1982).

The basic concept of the SAGE method is that a system of accounts with characteristic attributes is used as the decision factors. A relative importance coefficient (RIC) must be derived for each attribute within each account. The RIC for each attribute is calculated using a scoring procedure of attributes in an account involving pairwise comparisons of all combinations (Dean and Nishry, 1965). The procedure ensures that the sum of the RICs within each account is unity. An aggregate index of the account score for an objective is obtained by taking a linear combination of the scaled effects of the attributes where each attribute is weighted by its RIC. This last step can be summarized mathematically as:

$$X_{ij} = \sum_{k} (RIC_{jk}) (G_{ijk})$$

where (RIC_{jk}) is the relative importance coefficient for attribute k under the j^{th} objective, (G_{ijk}) is the effect of the i^{th} alternative on each attribute, and X_{ij} is the scaled score of the i^{th} alternative on the j^{th} objective. As noted earlier, the importance weighting approach used by Hyman, Moreau and Stiftel (1982) was the same as that used by Dean and Nishry (1965). Hyman, Moreau and Stiftel (1982) noted that the approach has some limitations. For example, the largest RIC that can be assigned to any attribute is (2/n), where n is the number of attributes. Also, the entire importance weighting process relies heavily upon expert judgment. Nonetheless, when accompanied by an explanatory text and a full description of the actual effects, the method can be useful for summarizing and comparing features of alternatives.

The unique aspect of the SAGE method is that there is weighting of the accounts relative to each other. For example, Table VIII.1 lists four major decision factors (health risk, economic efficiency, social concerns, and environmental impacts) which would be called accounts in the SAGE method. Attributes within an account listed in Table VIII.1 include biophysical, cultural, and socio-economic impacts. The SAGE method elicits weights between accounts by a technique based on social judgment theory (Hyman, Moreau, and Stiftel, 1982). The technique involves presenting respondents with an identical set of cards. Each card in the deck contains a verbal description of the effects of an alternative on each of the decision factors, as well as the scaled numerical scores for all of the accounts. In this Q-sort procedure, the participants are asked to arrange the cards in order of their preferences and then to score the alternatives on a scale ranging from 0 to 100.

Next, the analyst infers the weights from these rankings through the use of regression analysis methods. To do so, it is necessary to hypothesize a model that relates each participant's rankings of an alternative on an interval scale to the contribution of the alternative to each of the objectives. In mathematical terms,

$$Y_i = f(X_{i1}, X_{i2}, X_{i3}, X_{i4}, \ldots \ldots X_{in})$$

where Y_i is the score assigned to the i^{th} alternative and the variables X_{i1} to X_{in} refer to the contributions of the i^{th} alternative to the n objectives. In estimating the model, an error term is added to reflect inconsistencies in the participant's application of the model and also failures of the model to replicate a participant's actual weighting process. The simplest form of the regression model is linear:

$$Y_i = a + b_1X_{i1} + b_2X_{i2} + \ldots b_nX_{in} + e_i$$

where a is a constant, the b variables are weights attached to each of the n objectives, and e_i is the error term. Given a set of n alternatives and data on the X variables and Y_i for the set of participants, the analyst can infer the weights and perform an analysis of variance. If there is reason to believe that the rankings include nonlinearities or interactions, a more complex, polynomial model can be used instead.

Ranked Paired Comparison Techniques

The key feature of ranked pairwise comparison techniques relative to unranked techniques is that an initial ranking of all decision factors is required. Two examples of the use of ranked pairwise comparisons in environmental impact studies will be cited. The first deals with importance weighting for water resources projects (Dee, et al., 1972), and the second with importance weighting for a waterway navigation project (School of Civil Engineering and Environmental Science and Oklahoma Biological Survey, 1974). These examples could be adapted for usage in selecting an aquifer restoration strategy.

The general methodology developed for water resources projects is called the Environmental Evaluation System (EES). The relative importance of the 78 parameters in the EES was expressed in commensurate units, called parameter importance units (PIU), by quantifying several individuals' subjective value judgments. The weighting technique used by the method developers, Battelle-Columbus, was based on socio-psychological scaling techniques and the Delphi procedure (Dee, et al., 1972). The Delphi procedure will be discussed later. The importance weighting technique in the EES is systematic, minimizes individual bias, produces consistent comparisons, and aids in the convergence of judgment.

The ranked pairwise comparison technique used by Battelle-Columbus is a commonly-used socio-psychological scaling technique. In ranked pairwise comparison, the list of decision factors (or parameters) to be compared is ranked according to selected criteria and then successive pairwise comparisons are made between contiguous parameters to select for each parameter pair the degree of difference in importance. A weighted list of the parameters is the output from this procedure. The initial ranking was made based on considering the following three criteria relative to each parameter (decision factor):

(1) Inclusiveness of parameter

(2) Reliability of parameter measurements

(3) Sensitivity of parameter to changes in the environment

It should be noted that the 78 parameters are basically environmental parameters grouped into four categories (ecology, environmental pollution, aesthetics, and human interest) and 17 quantitative components (species and populations, habitats and communities, water pollution, air pollution, land pollution, noise pollution, land, air, water, biota, manufactured objects, composition, educational/scientific packages, historical packages, cultures, mood/atmosphere, and life patterns) as shown in Figure VIII.3 (Dee, et al., 1972). The following 10 steps were used in the importance weighting technique:

(1) Step 1: Select a group of individuals for conducting the evaluation and explain to them in detail the weighting concept and the use of their rankings and weightings.

(2) Step 2: Rank the categories, components, or parameters that are to be evaluated.

(3) Step 3: Assign a value of 1 to the first category on the list. Then compare the second category with the first to determine how much the second is worth compared to the first. Express this value as a decimal ($0 < x \leq 1$).

(4) Step 4: Continue with these pairwise comparisons until all in the list have been evaluated (Compare 3rd with 2nd, 4th with 3rd, etc.)

(5) Step 5: Multiply out percentages and express over a common denominator, and average overall individuals in the experiment.

(6) Step 6: In weighting the categories or components, adjust the decimal values from Step 5 if unequal numbers of parameters exist in the parameter groups being evaluated. Adjustment is made by proportioning these decimal values in proportion to the number of parameters included in that grouping.*

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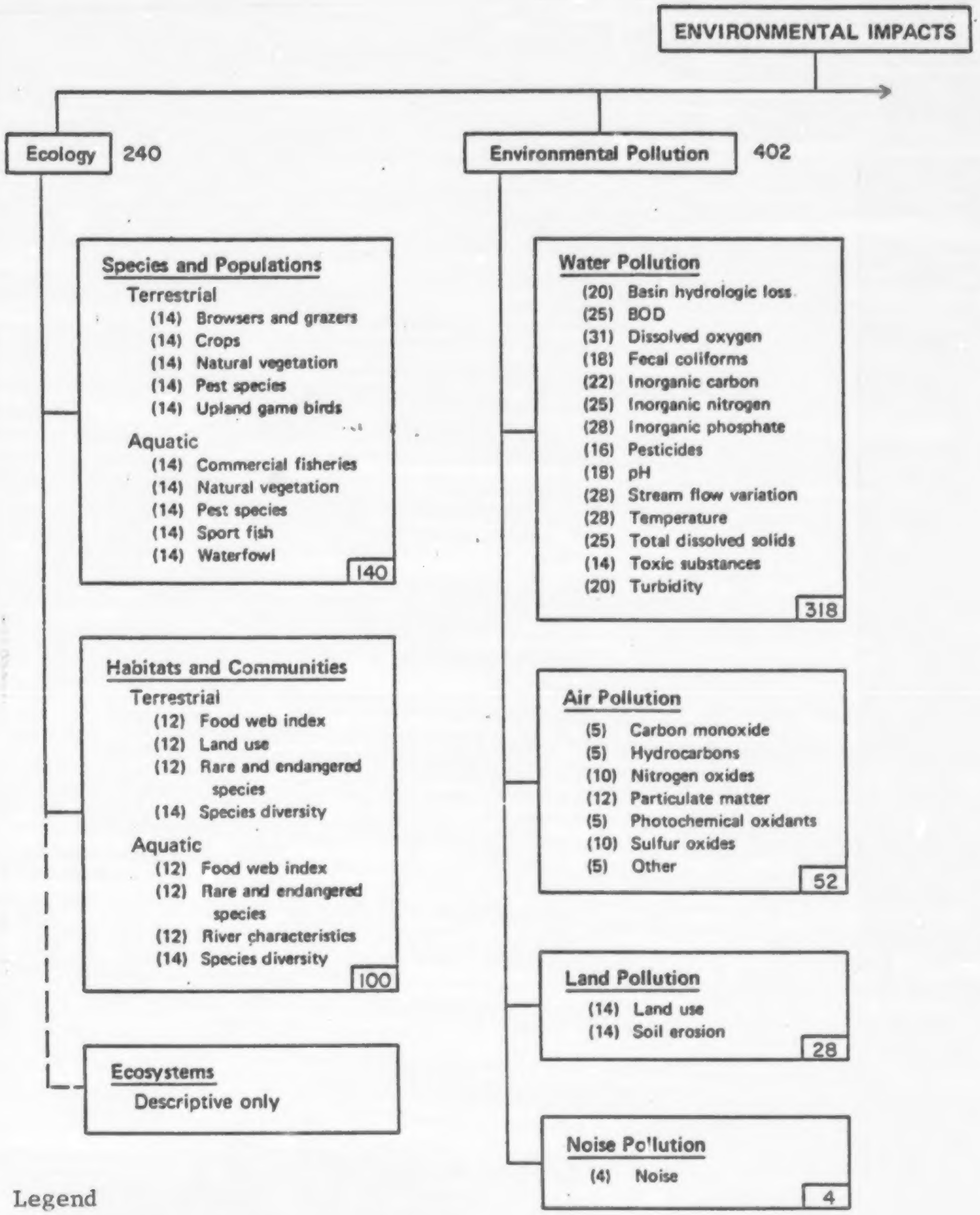
*The hierarchical system shown in Figure VIII.3 has an unequal number of elements in each grouping. To be mathematically correct all levels of the EES hierarchy should have an equal number of elements. However, at the present time, there has not been sufficient knowledge in many of


ENVIRONMENTAL IMPACTS
Ecology 240
Environmental Pollution 402
Species and Populations
Terrestrial
(14) Browsers and grazers
(14) Crops
(14) Natural vegetation
(14) Pest species
(14) Upland game birds
Aquatic
(14) Commercial fisheries
(14) Natural vegetation
(14) Pest species
(14) Sport fish
(14) Waterfowl
140
Habitats and Communities
Terrestrial
(12) Food web index
(12) Land use
(12) Rare and endangered species
(14) Species diversity
Aquatic
(12) Food web index
(12) Rare and endangered species
(12) River characteristics
(14) Species diversity
100
Ecosystems
Descriptive only
Water Pollution
(20) Basin hydrologic loss
(25) BOD
(31) Dissolved oxygen
(18) Fecal coliforms
(22) Inorganic carbon
(25) Inorganic nitrogen
(28) Inorganic phosphate
(16) Pesticides
(18) pH
(28) Stream flow variation
(28) Temperature
(25) Total dissolved solids
(14) Toxic substances
(20) Turbidity
318
Air Pollution
(5) Carbon monoxide
(5) Hydrocarbons
(10) Nitrogen oxides
(12) Particulate matter
(5) Photochemical oxidants
(10) Sulfur oxides
(5) Other
52
Land Pollution
(14) Land use
(14) Soil erosion
28
Noise Pollution
(4) Noise
4

Legend

( ) Parameter Importance Units
☐ Total

Figure VIII.3: Environmental Evaluation System (Dee, et al., 1972)

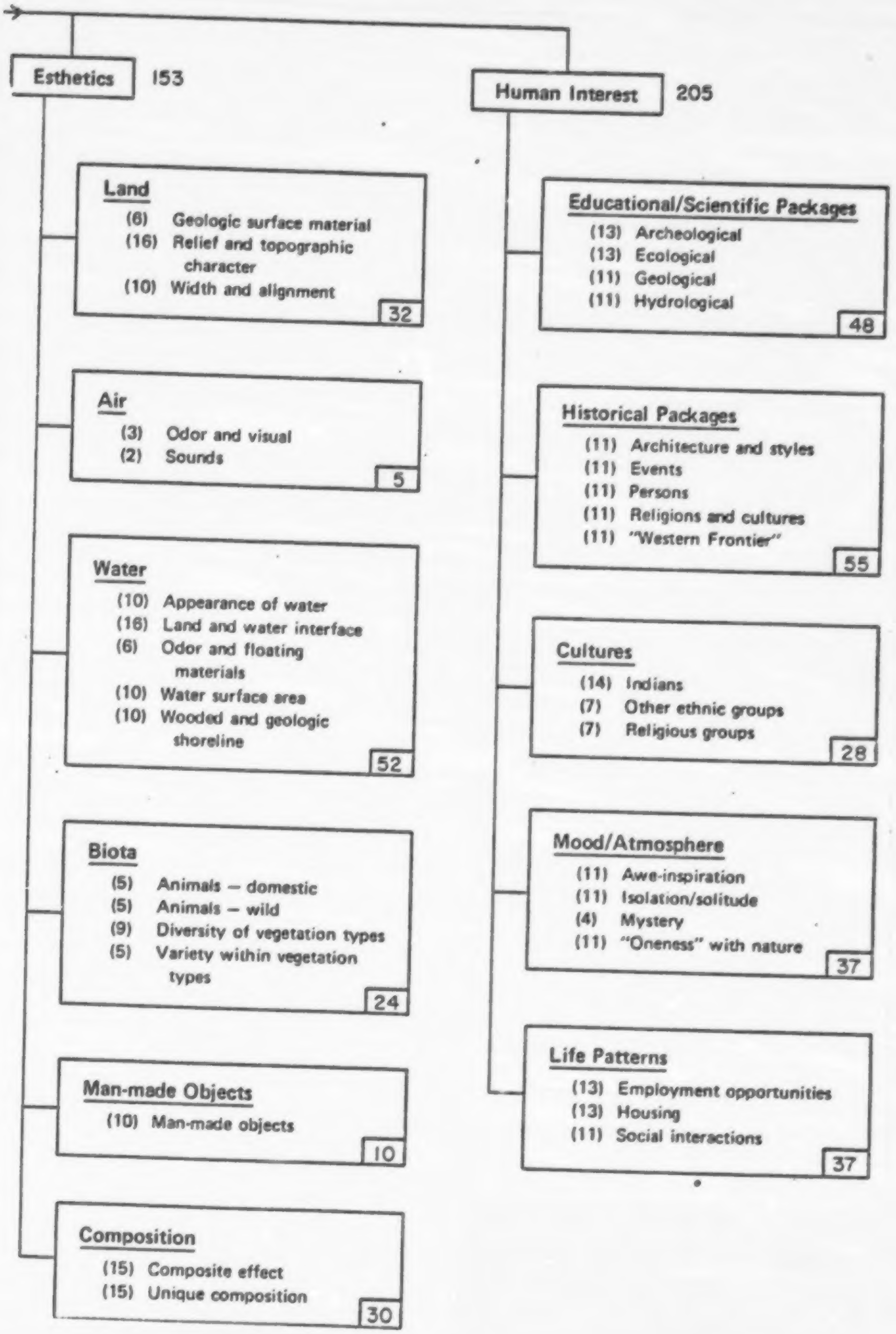

Esthetics
153
Land
(6) Geologic surface material
(16) Relief and topographic character
(10) Width and alignment
32
Air
(3) Odor and visual
(2) Sounds
5
Water
(10) Appearance of water
(16) Land and water interface
(6) Odor and floating materials
(10) Water surface area
(10) Wooded and geologic shoreline
52
Biota
(5) Animals — domestic
(5) Animals — wild
(9) Diversity of vegetation types
(5) Variety within vegetation types
24
Man-made Objects
(10) Man-made objects
10
Composition
(15) Composite effect
(15) Unique composition
30
Human Interest
205
Educational/Scientific Packages
(13) Archeological
(13) Ecological
(11) Geological
(11) Hydrological
48
Historical Packages
(11) Architecture and styles
(11) Events
(11) Persons
(11) Religions and cultures
(11) "Western Frontier"
55
Cultures
(14) Indians
(7) Other ethnic groups
(7) Religious groups
28
Mood/Atmosphere
(11) Awe-inspiration
(11) Isolation/solitude
(4) Mystery
(11) "Oneness" with nature
37
Life Patterns
(13) Employment opportunities
(13) Housing
(11) Social interactions
37

Figure VIII.3: (continued)

(7) Step 7: Multiply these averages by the number of parameter importance units to be distributed to the respective grouping.

(8) Step 8: Do Steps 2-7 for all categories, components, and parameters in the EES.

(9) Step 9: Indicate to the individuals by controlled feedback the group results of the weighting procedure.

(10) Step 10: Repeat the experiment with the same group of individuals or another group to increase the reliability of the results.

The following numerical example illustrates the use of the 10 steps (Dee, et al., 1972). Consider three components (A, B, C) that have been selected in Steps 1 and 2, with these components consisting of 8 parameters, 4 in A, 2 in B, and 2 in C.

Step 2	Ranking of component - B, C, A
Steps 3,4	Assigns weights B = 1 C = 1/2 the importance of B A = 1/2 the importance of C
Step 5	Multiply out percentages and express over common denominator. Assume the average values of all individuals are given below.

---

these areas to permit an equal number of elements at the same level of detail. This difference in the number of elements from group to group must be taken into consideration when assigning parameter importance units in the ranking and weighting. Therefore, in the ranking and weighting procedure (Steps 1-5), the researchers were asked to assume an equal number of elements in the groupings being compared. These value judgments were then "adjusted" in proportion to the number of elements in each group. Because the purpose of the weighting procedure was to assign weights to parameters, if an "adjustment" were not made the individual parameters grouped under water pollution would not receive sufficient weight as compared to those under noise because the total number of units available under water pollution would have to be distributed among 14 parameters whereas those for noise would all be assigned to the single noise parameter. For this reason, comparisons between components and categories should be based on average values of the PIU for the grouping not the sum of the values.

B = 1
C = .5
A = .25
1.75

B = 1/1.75 = .57
C = .5/1.75 = .29
A = .25/1.75 = .14
1.00

Step 6 Adjust for unequal number of parameters in each component.

B = .57 x 1/4 = .14
C = .29 x 1/4 = .07
A = .14 x 1/2 = .07
.28

Using the new total, the components values are

B = .14/.28 = .50
C = .07/.28 = .25
A = .07/.28 = .25
1.00

and the average values are

B = .50/2 = .25
C = .25/2 = .135
A = .25/4 = .0625

Step 7 Multiply these adjusted values by appropriate PIU, which is assumed in this case to be 20.

20 x .5 = 10
20 x .25 = 5
20 x .25 = 5

Step 8 Continue until reliable estimates are obtained.

In the EES, a total of 1000 PIU's are assigned to the parameters by first distributing to the 4 categories, then to the 17 quantitative components, and finally, to the 78 parameters. That is, the participating group specifies, for example, which is more important, aesthetics or environmental pollution, and then assigns appropriate weights. The process is continued until all the units are distributed among all parameters. Dee, et al. (1972) noted that instead of using the initial weight resulting from the importance weighting procedure, an aggregate weight based on several iterations of the technique is preferred. After each iteration, the participants are given selected information about the group weights. This information can include the group mean and variance, or other pertinent information. In the weighting procedure employed in developing the EES, the participants' mean value was given in the feedback stage. All of the weighting and feedback was performed via formal feedback statements, thereby avoiding undesirable direct interchange of judgments of the individuals in the test.

The waterway navigation project included an evaluation of the environmental impacts of 9 alternatives (8 waterway locational routes and the no-action alternative) for extending waterway navigation from Tulsa, Oklahoma to Wichita, Kansas (School of Civil Engineering and Environmental Science and Oklahoma Biological Survey, 1974). Figure VIII.4 presents a flow diagram of the environmental analysis approach used in the study. The multidisciplinary team consisted of an environmental engineer, botanist, zoologist, planner, and archaeologist. Six basic environmental categories were selected, and a total of 102 specific parameters were identified and grouped into the categories. The categories and parameters are listed in Table VIII.12 (School of Civil Engineering and Environmental Science and Oklahoma Biological Survey, 1974).

The research team discussed the six categories and agreed to following rank order of decreasing importance: biology; physical

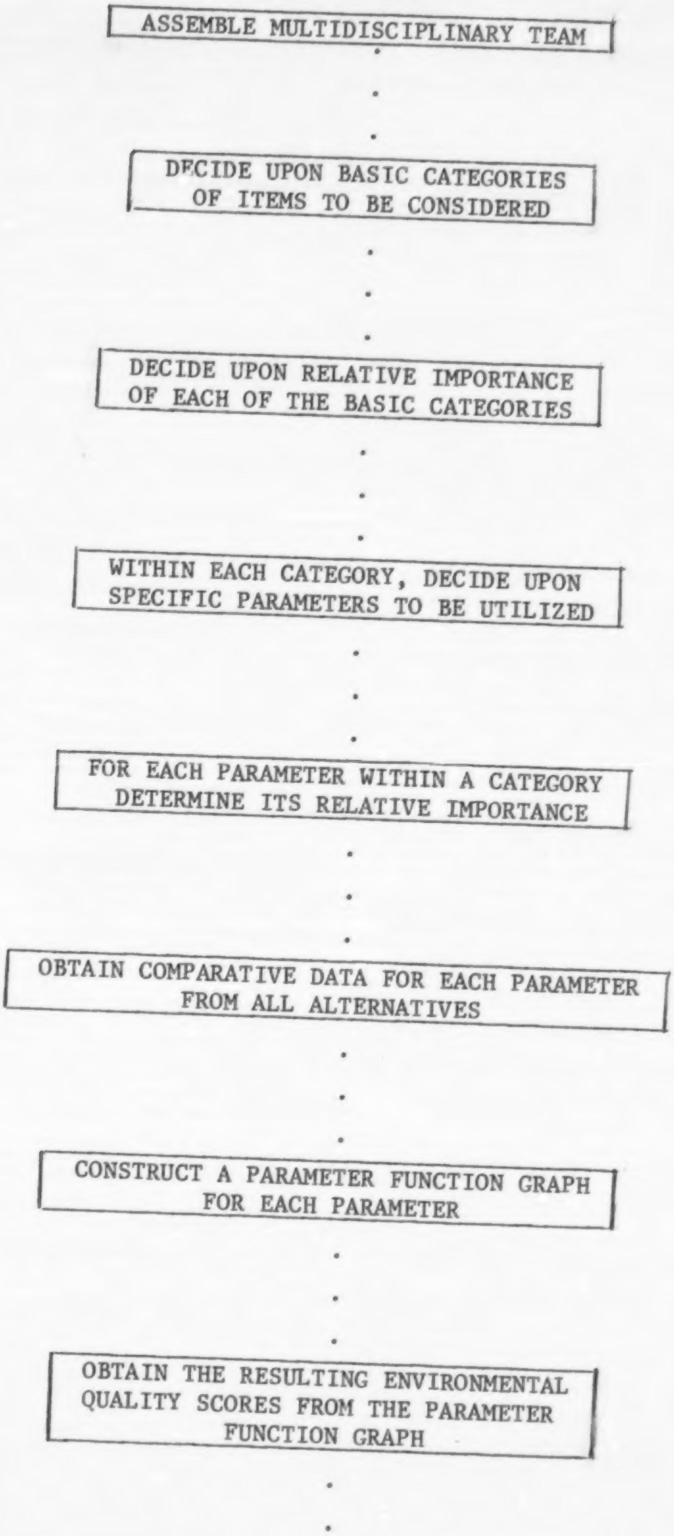
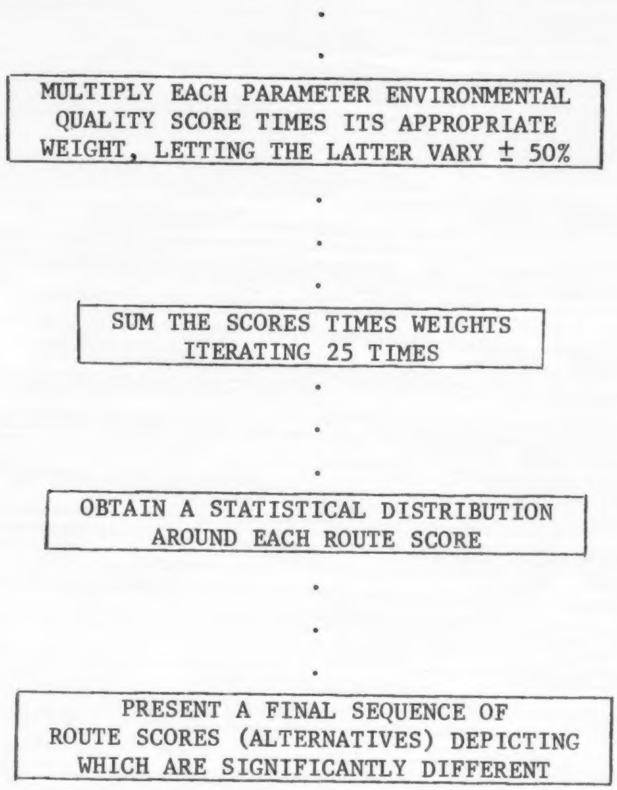

ASSEMBLE MULTIDISCIPLINARY TEAM
DECIDE UPON BASIC CATEGORIES OF ITEMS TO BE CONSIDERED
DECIDE UPON RELATIVE IMPORTANCE OF EACH OF THE BASIC CATEGORIES
WITHIN EACH CATEGORY, DECIDE UPON SPECIFIC PARAMETERS TO BE UTILIZED
FOR EACH PARAMETER WITHIN A CATEGORY DETERMINE ITS RELATIVE IMPORTANCE
OBTAIN COMPARATIVE DATA FOR EACH PARAMETER FROM ALL ALTERNATIVES
CONSTRUCT A PARAMETER FUNCTION GRAPH FOR EACH PARAMETER
OBTAIN THE RESULTING ENVIRONMENTAL QUALITY SCORES FROM THE PARAMETER FUNCTION GRAPH

Figure VIII.4: Flow Diagram of Environmental Analysis Procedure (School of Civil Engineering and Environmental Science and Oklahoma Biological Survey, 1974).



MULTIPLY EACH PARAMETER ENVIRONMENTAL QUALITY SCORE TIMES ITS APPROPRIATE WEIGHT, LETTING THE LATTER VARY ± 50%

SUM THE SCORES TIMES WEIGHTS ITERATING 25 TIMES

OBTAIN A STATISTICAL DISTRIBUTION AROUND EACH ROUTE SCORE

PRESENT A FINAL SEQUENCE OF ROUTE SCORES (ALTERNATIVES) DEPICTING WHICH ARE SIGNIFICANTLY DIFFERENT

Figure VIII.4: (Continued)

Table VIII.12: Environmental Categories and Parameters for Waterway Navigation Project (School of Civil Engineering and Environmental Science and Oklahoma Biological Survey, 1974)

Category	Parameter
Biology	1. Biological effect of water quality change
	2. Biological effect of salinization change
	3. Biological effect of eutrophication change
	4. Biological implications of siltation
	5. Browser populations (deer)
	6. Change from lotic to lentic habitat
	7. Changes in lowland feeding and breeding habitats
	8. Changes in lowland nesting habitat
	9. Expansion of population ranges
	10. Fishing pressure
	11. Food web index
	12. Grazers (cattle)
	13. Interruption of wildlife refuges
	14. Forest land removed
	15. Cropland removed
	16. Grassland removed
	17. Migration of waterfowl
	18. Miles of new shoreline (channel)
	19. Miles of new shoreline (lake)
	20. Number of oxbow lakes
	21. Pest species
	22. Potential areas for fish and wildlife management
	23. Potential for recreation areas
	24. Potential for sport and commercial fishing
	25. Rare and endangered species (plants and animals)
Physical/Chemical	26. Recruitment from tributaries
	27. Size of oxbow lakes
	28. Terrestrial ecosystem stability or diversity
	29. Unique habitats
	30. Weedy aquatic vegetation
	31. Weedy terrestrial vegetation
	32. Air pollution from construction
	33. Alteration of waste assimilative capacity
	34. Blasting and drilling (noise and dust)
	35. Change in appearance of water
	36. Change in salt load carried by stream
	37. Change in sediment load carried by stream
	38. Commitment of resources

Table VIII.12: (Continued)

	39. Degree of change in natural surface drainage
	40. Depth of cuts and effect on natural setting
	41. Flow modification and reduction in flood damage
	42. Increase in evaporation
	43. Miles of new stream
	44. Number of acres of land lost
	45. Number and type of new bridges
	46. Number of lakes created
	47. Number of locks and route distance (travel time in route)
	48. Number of recreational areas developed and the resulting pollution
	49. Noise from operation
	50. Other noise from construction
	51. Pollution from shipping
	52. Potential for affecting municipal pollution
	53. Potential for shipping accident
	54. Relocations (utilities, railroads, highways)
	55. Size of work force and effects of temporary camps
	56. Susceptibility of cuts to erosion
	57. Total quantity of excavation
	58. Water and air pollution resulting from industrialization
Regional Compatibility	59. Accessibility to first order transportation (non-rail)
	60. Accessibility to railroad transportation
	61. Accessibility to second order transportation
	62. Conformance to existing and developing urban patterns
	63. Construction-intermediate urban to site distance (impact of construction phase)
	64. Construction-major urban to site distance (impact of construction phase)
	65. Construction-minor urban to site distance (impact of construction phase)
	66. Proximity to urban centers (intermediate)
	67. Proximity to urban centers (major)
	68. Proximity to urban centers (minor)
	69. Severance of surface transport routes
Archeology	70. Age or occupational period of the site
	71. Concern by local population
	72. Cost of conducting on foot archaeological survey
	73. Depth of the occupational area
	74. Ecological setting

Table VIII.12: (Continued)

	75. Eligibility of the site for state or national register
	76. Estimated number of sites to be obtained by the survey
	77. Importance in terms of local, state, and national level
	78. Minimum salvage costs for estimated sites
	79. Nature of the site
	80. Number of known sites to be damaged
	81. Presence of single or multiple occupations
	82. Preservation of archaeological data
	83. Previous knowledge of the area
	84. Site frequency within the area concerned
	85. Site importance in terms of geographic area and problems
	86. Site preservation or damages
	87. Size of occupational area
	88. Value of site for non-archaeological fields
Aesthetics	89. Atmospheric turbidity
	90. Confinement of view
	91. Degree of alteration of natural setting
	92. Degree of urbanization
	93. Diversity of vegetation types
	94. Landform diversity
	95. Man-made visual obstructions
	96. River pattern (channelization)
	97. Turbidity
	98. Wildlife diversity
Climatology	99. Increase in fog frequency
	100. Changes in microclimates (± 1 mile)
	101. Evaporative potential
	102. Inadvertent weather modification

chemical, regional compatibility, archaeology, aesthetics, and climatology. A total of 1000 importance points (or weights) were distributed by the ranked pairwise comparison technique as used in the EES (Dee, et al., 1972). In most cases within a category, the parameters were classified as to high, medium, or low importance, and the allotted points for that particular category were distributed accordingly. High importance parameters were allotted three times as many points as low importance parameters, and medium importance parameters were allotted twice as many points as the low importance parameters.

Evaluation of the 9 alternatives in the waterway navigation project relative to the 78 parameters was made via the use of parameter function graphs yielding environmental quality (EQ) scores. Development and usage of the graphs will be discussed later. The overall impact evaluation was made via the development of Route Scores for each alternative, with the Route Scores defined as follows (School of Civil Engineering and Environmental Science and Oklahoma Biological Survey, 1974):

$$\text{Route Score}_j = \sum_{i=1}^{102} (EQ)_{ij}\ IW_i$$

where:

EQ_{ij} = environmental quality for jth alternative relative to ith parameter.

IW_i = importance weight of ith parameter.

Since the importance weights for the 6 categories and 102 parameters involved considerable subjective judgment, the weight term in the above Route Score equation was allowed to vary randomly (± 50%) in calculating Route Scores. A computer program was used to calculate an average route score following 25 iterations of the above equation.

DELPHI TECHNIQUE FOR IMPORTANCE WEIGHTING

The Delphi technique is a structured approach for achieving group concensus about common issues of concern. It was used in a modified form in the development of importance weights in the EES described earlier (Dee, et al., 1972). The Delphi technique has been compared to other group communication techniques as shown in Table VIII.13 (Linstone and Turoff, 1975). Conventional Delphi is the method discussed herein, while real time Delphi, that is, computer conferencing, refers to a variation of conventional Delphi. The technique has broad versatility and the results are easy to understand. Application of the method involves a few days to as much as three months which makes the cost low to medium compared to other methods. The expertise required to administer the study ranges from very little to average and the assistance required ranges from none to highly sophisticated computer data analysis (Stanford Research Institute, 1975). The Delphi technique could be used to weight decision factors associated with the selection of an aquifer restoration strategy for meeting a given need.

Key elements in the successful conduction of a Delphi study are the study director and the chosen panel of experts. The panel of experts chosen may come from academic, governmental, consulting or industrial backgrounds (Toussaint, 1975; Martino, 1972). There are three other types of panelists: stakeholders (those directly affected), experts who can supply experience and special application techniques, and

Table VIII.13: Group Communication Techniques (Linstone and Turoff, 1975)

	Conference Telephone Call	Committee Meeting	Formal Conference or Seminar	Conventional Delphi	Real-Time Delphi
Effective Group Size	Small	Small to medium	Small to large	Small to large	Small to large
Occurrence of Interaction by Individual	Coincident with group	Coincident with group	Coincident with group	Random	Random
Length of interaction	Short	Medium to long	Long	Short to medium	Short
Number of Interactions	Multiple, as required by group	Multiple, necessary time delays between	Single	Multiple, necessary time delays between	Multiple, as required by individual
Normal Mode Range	Equality to chairman control (flexible)	Equality to chairman control (flexible)	Presentation (directed)	Equality to monitor control (structured)	Equality to monitor control or group control and no monitor (structured)
Principal Costs	Communications	-Travel -Individuals' time	-Travel -Individuals' time -Fees	-Monitor time -Clerical -Secretarial	-Communications -Computer usage
	Time-urgent considerations	Forced delays		Forced delays	Time-urgent considerations
Other Characteristics	-Equal flow of information to and from all -Can maximize psychological effects		-Efficient flow of information from few to many	-Equal flow of information to and from all -Can minimize psychological effects -Can minimize time demanded of respondents or conferees	

facilitators who can clarify, organize or stimulate (Linstone and Turoff, 1975). The director nominates outside experts based on a combination of their performance, years of experience, number of publications, and status with peers (Helmer, 1966). Expertise can also be assessed by contrasting it with public views of whomever is willing to buy and pay for each individual opinion. Those selected may be asked to nominate other panel members. The availability and willingness to serve for the entire study is an important consideration. The number of experts chosen is usually 7 to 10 for environmental issues, although more panelists are used in forecasting social impacts (Toussaint, 1975). Studies have shown that when employing a group to arrive at a decision, the average group error decreases with an increase in the number of individuals. As the panel increases in size there is an increase in reliability up to 15 panel members (Gordon and Helmer, 1964).

Several rounds of questionnaires are used in the conventional Delphi technique. The questionnaires may be prepared before or during the selection of panel members. Once the questionnaires have been designed and the panel selected, the next step is the administration of the Delphi sequence which involves the mailing of questionnaires and their return to the director. The director compiles and edits the information received for successive rounds.

If the Delphi technique is being used for importance weighting, the objective of round one is to get an initial estimate of the ranking and relative importance weights of the decision factors. The objective could be to identify potential decision factors given information about the environmental setting and potential project. The information generated in the first round must be carefully reviewed by the director and duplications eliminated. The director determines the median (point of concensus) and the spread of opinion which is expressed by the interquartile range (IQR) encompassing 25% of the responses above and below the median. The panelists receive this written feedback through the mail which eliminates the noise of an open discussion and the dominance of certain individuals in the panel.

In round two panelists weigh the strength of their own convictions against the group median and may even revise the ranking and relative importance of their round one estimates. Experts who give responses outside the IQR must write down their reasons. On the average, the questionnaire and written material for the second round will be five to ten times that of the first round (Linstone and Turoff, 1975). The developments are reordered by using a combination of probability, desirability, or feasibility scales. In many cases it may be desirable to keep track of certain subgroups making up the respondent group as a whole. This provides a mechanism to decide whether polarized views reflect the affilitations or the background of the respondents. The director compiles round two estimates and presents the new median, IQR, and reasons for their distribution in round three.

Round three is conducted similar to round two and again experts write down their reasons for disagreeing with estimates outside the new IQR. The initial disagreers and new ones have a chance to convince other panelists to change their estimates. The responses are summarized by median, IQR, disagreement reasons and counter arguments. If it is the last round, the director summarizes majority and minority opinions on projections for each development along with the above information before a re-vote is taken. If possible, the re-vote should be put off until a fourth round when everyone can see the additional remarks. In the fourth round a re-vote is taken and the director compiles the new median, IQR and reasons for consensus for each issue being addressed. Delphi studies could utilize two to five rounds, but it has been found that responses tend to stabilize after three rounds (Helmer, 1966). Four rounds may be necessary to give minority opinions a chance at shifting the median and IQR (Toussaint, 1975).

A number of major criticisms have been made against usage of the Delphi technique. Helmer (1966) identified the following criticisms:

(1) There is instability in the panel memberships. Many studies have shown that only a few of the panelists respond to questionnaires, many drop out on succeeding rounds, and convergence is impeded by too many panel substitutions.

(2) A big time lapse between succeeding rounds can cause shifting of opinions.

(3) Ambiguous questions confuse panelists.

(4) Panelists' competence is questionable. Helmer (1966) suggests asking experts questions only in their particular field and to leave blanks when unsure of their own judgment.

On the positive side, there are several things which can be done to improve the results of the use of the Delphi technique for importance weighting. Martino (1972) recommended the following eight steps to insure the smooth conduction and reliability of a Delphi study:

(1) Obtain agreement of experts to serve on a panel.

(2) Explain the Delphi procedure thoroughly.

(3) Avoid compound events in one analysis. If the event statement contains one part the panelist agrees with, and another part he disagrees with, it is difficult for him to know how to

answer. Avoid compound questions such as: Capability A will be achieved through the use of Technology B in the year ____. The panelist may find two distinct parts for a single event, and this is where feedback is valuable to help the director improve his questions.

(4) Avoid ambiguous statements of events, and the careless use of technical jargon. Avoid using the terms "everybody knows", "common", "widely used", "normal", and "in general use".

(5) Make questions easy to answer such as filling in the blank, or multiple choice. The arguments for and against each event should be summarized so the panelists can connect them to specific questions.

(6) Ask no more than 25 to 40 questions in any one Delphi round.

(7) The director should never inject his own opinion(s). If the director becomes convinced that the panelists are overlooking some significant element, he should recognize that he has picked an unqualified panel and should repeat the work with another panel.

(8) The director should be able to estimate the work load involved for each panel member in a Delphi sequence. As a planning factor, the director should allow two professional man-hours per panelist per questionnaire. When using 100 or more panelists it is advisable to use a computer to aid in the data analysis.

Linstone and Turoff (1975) have made other procedural recommendations which are stated below:

(1) Lay out the expected processing of the data throughout all the rounds of the Delphi before you finalize the design. You may be forced to later modify the procedure, but the process of planning ahead will usually turn up any large problems in your initial questionnaire design.

(2) Design the handling of data so that each response can be processed as it comes in. By doing this you will not have a frantic rush to analyze all the responses at once when the last return comes in.

(3) At least two professionals should work on monitoring a Delphi exercise, especially when the abstracting of comments is a good portion of the exercise. With two individuals one can always review what the other has done.

(4) Pretest your questionnaire on a group before using it for the rounds sequence.

(5) If you are covering a number of fields of expertise, make sure each field is adequately represented in your group.

(6) The criteria for retaining an item for further evaluation should be made clear at the beginning of the Delphi sequence.

(7) Interpersonal techniques such as interviews and seminars should be interspersed with the rounds of questionnaires and information feedback.

(8) When editing respondents comments, try to preserve the intent of the originator. When editing from round to round, avoid changing a statement so that it has one meaning in one round and another meaning in another round.

(9) Standardized measures should be available to a respondent so he can self-rate his competence or familiarity to specific questions.

(10) If a multidisciplinary approach is desired respondents should be encouraged to consider all items, but to make estimates only on those items with which he feels comfortable. Respondents may indicate their familiarity with a specialized area or the importance of an item, without making probability estimates.

(11) The source of a suggested item should be identified taking care not to compromise the anonymity of specific inputs. Keep track of how different subgroups in your respondent group vote on specific items. This can be very useful in analyzing the results and will produce situations where you want the respondents to know the existence of polarizations or differences based on particular backgrounds.

To serve as an example for an environmentally-related study, Toussaint (1975) used the Delphi technique to develop importance weights for 14 water pollution parameters related to the proposed Aubrey Reservoir project in northern Texas. Eighteen environmental experts from the region established regional values for the two judgment-based decisions currently used in environmental impact assessment. These two decisions were referred to as the weighting (determination of the relative emphasis or degree of importance each parameter is to be assigned in the assessment) and scaling (determination of the magnitude of effect resulting from a change in a parameter measure) process. The Delphi procedure was used to reach a consensus of opinion.

SCALING/RATING/RANKING OF ALTERNATIVES

Scaling/rating/ranking of each alternative for each decision factor is the second major aspect in the use of the multiple-criteria decision-making approach. Several different techniques have been used for this evaluation of alternatives in a decision. Examples of techniques which have potential applicability to decisions related to the selection of an aquifer restoration strategy for meeting a given need include the use of (1) the alternative profile concept, (2) a reference alternative, (3) linear scaling based on the maximum change, (4) letter or number assignments designating impact categories, (5) evaluation guidelines, (6) functional curves, or (7) the paired-comparison technique. Examples of each of these techniques are as follows:

(1) Bishop, et al., (1970) contains information on the alternative profile concept for impact scaling. This concept is represented by a graphical presentation of the effects of each alternative relative to each decision factor. Each profile scale is expressed on a percentage basis ranging from a negative to a positive 100%, with 100% being the maximum absolute value of the impact measure adopted for each decision factor. The impact measure represents the maximum change, either plus or minus, associated with a given alternative being evaluated. If the decision factors are displayed along with the impact scale from +100% to -100%, a dotted line can be used to connect the plotted points for each alternative and thus describe its "profile". The alternative profile concept is useful for visually displaying the relative impacts of a series of alternatives.

(2) Salomon (1974) describes a scaling technique for evaluation of cooling system alternatives for nuclear power plants. To

determine scale values, a reference cooling system was used and each alternative system compared to it. The following scale values were assigned to the alternatives based on the reference alternative: very superior (+8), superior (+4), moderately superior (+2), marginally superior (+1), no difference (0), marginally inferior (-1), moderately inferior (-2), inferior (-4), and very inferior (-8).

(3) Odum, et al., (1971) utilized a scaling technique in which the actual measures of the decision factor for each alternative plan are normalized and expressed as a decimal of the largest measure for that factor. This represents linear scaling based on the maximum change.

(4) A letter scaling system is used in Voorhees and Associates (1975). This methodology incorporates 80 environmental factors oriented to the types of projects conducted by the Department of Housing and Urban Development. The scaling system consists of the assignment of a letter grade from A+ to C- for the impacts, with A+ representing a major beneficial impact and C- an undesirable detrimental change.

(5) Duke, et al., (1977) describe a scaling checklist for the EQ account for water resources projects. Scaling is accomplished following the establishment of an evaluation guideline for each environmental factor. An evaluation guideline is defined as the smallest change in the highest existing quality in the region that would be considered significant. For example, assuming that the highest existing quality for dissolved oxygen in a region is 8 mg/l, if a reduction of 1.5 mg/l is considered as significant, then the evaluation guideline is 1.5 mg/l irrespective of the existing quality in a given regional stream. Scaling is accomplished by quantifying the impact of each alternative relative to each environmental factor, and if the net change is less than the evaluation guideline it is insignificant. If the net change is greater and moves the environmental factor toward its highest quality, then it is considered to be a beneficial impact; the reverse exists for those impacts that move the measure of the environmental factor away from its highest existing quality.

(6) A paired-comparison technique can also be used for assigning scale values to alternatives based on their impact on environmental factors. The paired comparison technique for accomplishing scaling is described in Dean and Nishry (1965).

(7) Functional curves can also be used to accomplish impact scaling for environmental factors. The functional curve is used to relate the objective evaluation of an environmental factor to a subjective judgment regarding its quality based on a range from high to low quality (Dee, et al., 1972).

Paired Comparison Technique for Scaling/Rating/Ranking

One of the most useful techniques for scaling/rating/ranking of alternatives relative to each decision factor is the paired-comparison technique described by Dean and Nishry (1965). This technique was also described earlier relative to its use for importance weighting of decision factors. Again, this technique can be used by an individual or group for the scaling/rating/ranking of alternatives. Suppose that the decision to be made involves four decision factors and that the importance weights have been assigned as shown in Table VIII.8. Furthermore, suppose that there are three alternatives (A1, A2, and A3) to be evaluated relative to the four decision factors, and that Table VIII.14 contains the relevant qualitative and quantitative information. The scaling/rating/ranking technique consists of considering each alternative relative to every other alternative and assigning to the one of the pair considered to be the most desirable a value of 1, and to the lesser desirable of the pair a value of 0. The use of this paired comparison technique for the three basic alternatives and four basic decision factors is shown in Tables VIII.15 through VIII.18, respectively. It should be noted that the assignment of 0 to a member of a pair does not denote zero desirability; it simply means that in the pair considered it is of lesser desirability.

A dummy alternative, called A4, is also included in Tables VIII.15 through VIII.18. The dummy alternative is included so as to preclude the net assignment of a value of 0 to any of the basic alternatives (A1 through A3) in the process of each paired comparison. The dummy alternative is defined as the least desirable in each paired comparison

Table VIII.14: Information for Trade-off Analysis

Decision Factor	Alternatives A1	 A2	 A3
F1	Has lowest health risk	Has highest health risk	Has medium degree of health risk
F2	Medium economic efficiency	Low economic efficiency	High economic efficiency
F3	Undesirable social impacts expected	No social impacts expected	Beneficial social impacts expected
F4	Decrease overall environmental quality by 20%	Increase overall environmental quality by 10%	Increase overall environmental quality by 10%

Table VIII.15: Scaling/Rating/Ranking of Alternatives Relative to F1

Alternative	Assignment of Desirability						Sum	ACC
A1	1	1	1				3	0.50
A2	0			0	1		1	0.17
A3		0		1		1	2	0.33
A4 (dummy)			0		0	0	0	0
							6	1.00

Table VIII.16: Scaling/Rating/Ranking of Alternatives Relative to F2

Alternative	Assignment of Desirability						Sum	ACC
A1	1	0	1				2	0.33
A2	0			0	1		1	0.17
A3		1		1		1	3	0.50
A4 (dummy)			0		0	0	0	0
							6	1.00

Table VIII.17: Scaling/Rating/RAnking of Alternatives Relative to F3

Alternative	**Assignment of Desirability**						**Sum**	**ACC**
A1	**0**	**0**	**1**				**1**	**0.17**
A2	**1**			**0**	**1**		**2**	**0.33**
A3		**1**		**1**		**1**	**3**	**0.50**
A4 (dummy)			**0**		**0**	**0**	**0**	**0**
							6	**1.00**

Table VIII.18: Scaling/Rating/Ranking of Alternatives Relative to F4

Alternative	**Assignment of Desirability**						**Sum**	**ACC**
A1	**0**	**0**	**1**				**1**	**0.17**
A2	**1**			**0.5**	**1**		**2.5**	**0.415**
A3		**1**		**0.5**		**1**	**2.5**	**0.415**
A4 (dummy)			**0**		**0**	**0**	**0**	**0**
							6.0	**1.00**

within which it is included. If two alternatives have the same desirability relative to a decision factor (one is not more desirable than another), then a value of 0.5 is assigned to each of the pair.

Following the assignment of the relative desirability of each alternative relative to each other alternative, with this process based on the qualitative and quantitative information in Table VIII.14, then individual choice assignments are summed, with the alternative choice coefficient (ACC) being equal to the sum value for an individual alternative divided by the sum for all of the alternatives. The total of the sum column in Tables VIII.15 through VIII.18 should equal to (M)(M-1)/2 where M is equal to the number of alternatives included in the assignments. In this example, four alternatives were included, hence the sum column total in Tables VIII.15 through VIII.18 should be equal to 6. The total of the ACC column should equal to 1.00.

The ACC column in Table VIII.15 indicates that alternative A1 is the most desirable relative to decision factor F1, and is followed by A3 and A2. Similar types of comments could be made for the ACC values in Tables VIII.16 through VIII.18. Whether or not the actual ACC fractions are used in a trade-off analysis, this paired-comparison approach has enabled the rank ordering of the desirability of each alternative relative to each decision factor. As noted earlier, the paired-comparison technique based on Dean and Nishry (1965), including the development of both FIC and ACC values, has been used in a number of environmentally-related studies (Morrison, 1974; Canter, 1976; Solomon, et al., 1977; and Canter and Reid, 1977). This technique could be easily applied to decision-making needs associated with the selection of an aquifer restoration strategy for meeting a given need.

Functional Curves for Scaling/Rating/Ranking

Functional curves, also called value functions and parameter function graphs, have been used in a number of environmental impact studies for scaling/rating/ranking the impacts of alternatives relative to a series of decision factors. They have potential for application in aquifer restoration programs. Dee, et al. (1972) described the following seven steps which could be used in developing a functional curve (relationship) for an environmental parameter (decision factor):

(1) Step 1: Obtain scientific information when available on the relationship between the parameter and the quality of the environment. Also, obtain experts in the field to develop the value functions.

(2) Step 2: Order the parameter scale so that the lowest value of the parameter is zero and it increases in the positive directions -- no negative values.

(3) Step 3: Divide the quality scale (0-1) into equal intervals and express the relationship between an interval and the parameter. Continue this procedure until a curve exists.

(4) Step 4: Average the curves over all experts in the experiment to obtain a group curve. (For parameters based solely on judgment, value functions should be determined by a representative population cross section.)

(5) Step 5: Indicate to the experts doing the value function estimation the group curve and expected results of using the curves in the EES. Decide if a modification is desired; if needed go to Step 3, if not continue.

(6) Step 6: Do Steps 1-5 until a curve exists for all parameters.

(7) Step 7: Repeat experiment with the same group or another group of persons to increase the reliability of the functions.

The same basic approach as used by Dee, et al. (1972) was also described by Rau (1980). Parameter function graphs were also developed and used in the environmental impact study for the waterway navigation project (School of Civil Engineering and Environmental Science and Oklahoma Biological Survey, 1974). Examples of two functional curves are shown in Figures VIII.5 and VIII.6 (Dee, et al., 1972). Usage of the curves would involve entering the x-axis with extant or predicted information and reading the resultant y-axis environmental quality scale.

DEVELOPMENT OF DECISION MATRIX

The final step in multiple-criteria decision-making is to develop a decision matrix displaying the products of the importance weights (or ranks) and the alternative scales (or ranks). To complete the example using the paired-comparison technique (Canter, 1983), Table VIII.19 summarizes the FIC values for the 4 decision factors (from Table VIII.8), and the ACC values for the 3 alternatives (from Tables VIII.15 through VIII.18). The final product matrix is shown in Table VIII.20. Summation of the products for each alternative indicates that alternative A3 would be the best choice followed by A1 and A2. The bases for the differences in the three alternatives are indicated by the fractions shown in Table VIII.20.

Rau (1980) provided an illustration of using importance weighting and impact rating to develop a total impact evaluation for four alternatives. As described earlier, importance weighting involved a group approach using scales of importance. Table VIII.5 contains an

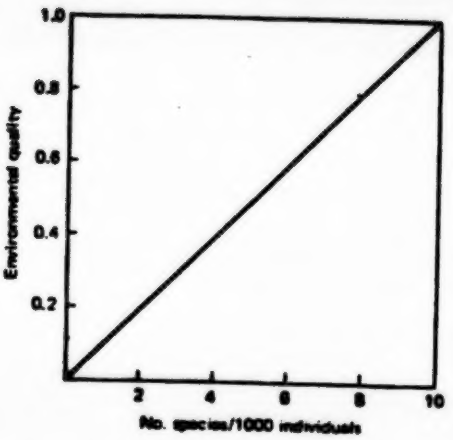


Figure VIII.5: Functional Curve for Species Diversity (Dee, et al., 1972).

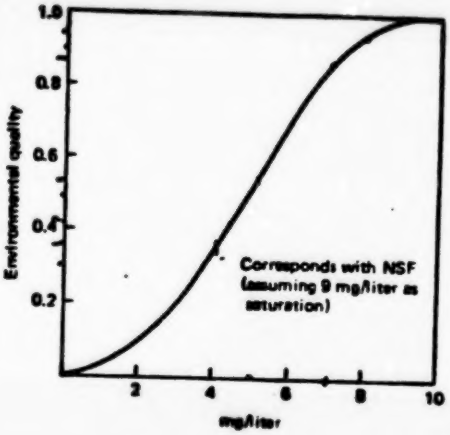


Figure VIII.6: Functional Curve for Dissolved Oxygen in Water (Dee, et al., 1972).

example of the use of this approach (Rau, 1980). Impact rating was used based on pre-defined values as shown in Table VIII.21 (Rau, 1980). The decision matrix is developed by multiplying each alternatives' impact ratings by the importance weights from each of the decision factors.

In the Battelle EES an overall environmental impact index is calculated based on the following two steps (Dee, et al., 1972):

(1) Obtain parameter data without the project for each of the 78 environmental factors. Convert these parameter data into EQ scale values for each of the 78 parameters. Multiply these scale values by the PIU for each of the individual parameters to develop a composite score for the environment without the project.

(2) For each alternative predict the change in the environmental parameters. Utilizing predicted changes in the parameter values, determine the environmental quality scale for each parameter and each alternative. Multiply the environmental quality values for each alternative by each PIU, and aggregate the information for a total composite score.

The overall impact evaluations approach used in the waterway navigation project was comprised of two parts (School of Civil Engineering and Environmental Science and Oklahoma Biological Survey, 1974). The first part, called Optimum Pathway Matrix Analysis (OPMA), uses a large number of data items from each route to derive a single value for each route on an arbitrary scale of 0 (low environmental quality) to 1000 (high environmental quality). The second part used is a multidimensional ordination of routes based on principal components analysis of parameter values (Jeffers, 1967). The ordination uses the data to construct a multidimensional ordering of the routes based on their similarity to each other rather than on some externally determined scale.

Table VIII.19: FIC and ACC Values for Example Decision Problems

Decision Factors	FIC Values	ACC Values		
		A1	A2	A3
F1	0.40	0.50	0.17	0.33
F2	0.20	0.33	0.17	0.50
F3	0.10	0.17	0.33	0.50
F4	0.30	0.17	0.415	0.415

Table VIII.20: Product Matrix for Trade-off Analysis for Example Decision Problem

	FIC x ACC		
Decision Factor	**A1**	**A2**	**A3**
F1	0.200	0.068	0.132
F2	0.066	0.034	0.100
F3	0.017	0.033	0.050
F4	0.051	0.124	0.124
	0.334	0.259	0.406

Table VIII.21: Basis for Impact Rating (Rau, 1980).

Impact on Present Condition	Value
≥ 100% increase	+7
50-99.9% increase	+5
25-49.9% increase	+3
0-24.9% increase	+1
No change	0
0-24.9% decrease	-1
25-49.9% decrease	-3
50-99.9% decrease	-5
≥ 100% decrease	-7

In the OPMA approach information from the importance weighting of 102 parameters was coupled with impact scaling information for the 102 parameters based on the use of parameter function graphs. As described earlier, Route Scores were developed for the 9 alternatives. The OPMA procedure was converted to a Fortran computer program which builds an n X m matrix consisting of the scaled parameter values for n routes with m components for each route. Each component vector is then multiplied by its weight and each route vector is summed, giving a score for each route. Since the weights were subjectively determined, each route score was calculated 25 times with a different random error between ± 50% introduced each time an importance weight was multiplied by a scaled parameter value. The random error was modified by a parabolic transformation of its frequency distribution such that the probability of an error greater than 45% is 0.02, while the probability of an error less than 5% is 0.2. Introduction of random errors and calculating each route score 25 times allows the calculation of confidence intervals and the use of statistical tests to determine whether differences between routes are significant.

The computer output for OPMA consisted of a list of scores for each route with the mean and confidence interal for that route, plus the results of a Student's T evaluation of the differences between routes, and a ranked list of the route scores. OPMA was done on each of the major categories (Biology, Physical/Chemical, Regional Compatibility, Archaeology, Aesthetics and Climatology) and on the total set of parameter values. In addition, OPMA was performed separately using parameters of high, medium and low importance. Finally, OPMA was done combining selected categories: Biology and Physical/Chemical; Biology, Physical/Chemical, Regional Compatibility, and Archaeology; and Biology, Physical/Chemical, Regional Compatibility, Archaeology and Aesthetics (School of Civil Engineering and Environmental Science and Oklahoma Biological Survey, 1974).

In the second part of the overall analysis of waterway navigation routes, a non-polar principal components-based ordination was constructed for the routes by the method of Jeffers (1967). In this case (1) the data consisted of the matrix of scaled parameter values; (2) the basic data were not transformed; (3) a correlation matrix was calculated; and (4) parameters with scaled eigenvector values having absolute values greater than 0.7 were used in the calculation of route positions. A standard library program (FACTO) was used to calculate the initial principal components analysis. Each eigenvector from the principal components analysis was used to calculate route positions on one axis of the ordination. Positions of the routes on an ordination axis were calculated by (1) scaling the elements of the corresponding eigenvector to a maximum value of +1.0; (2) deleting all component vectors having scaled eigenvectors with absolute values less than 0.7; (3) multiplying each of the remaining component vectors by its eigenvector; and (4) summing the route vectors to produce the route positions on the axis. The result of the ordination procedure is a multidimensional graphical representation of similarity between the routes (School of Civil Engineering and Environmental Science and Oklahoma Biological Survey, 1974).

The concepts of a weighting-scaling/rating/ranking approach as demonstrated in these example studies have been used in a number of other studies involving decisions which included environmental matters. Table VIII.22 contains a summary listing of these examples along with some other weighting-scaling checklists which have been used in environmental decision-making and impact assessment studies (Canter, 1979). The general steps associated with this type of approach for doing a trade-off analysis are outlined in Table VIII.23. These steps could be used to aid in decision-making associated with the selection of an aquifer restoration strategy for meeting a given need.

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Table VIII.22: Summary of Some Weighting-Scaling/Rating/Ranking Methods for Trade-off Analyses

Author(s)	**Salient Features**
Canter (1976)	Weighting-scaling checklist using weighted rankings technique is described.
Canter and Reid (1977)	A weighting-scaling technique for evaluating the environmental impact of wastewater treatment process is described.
Crawford (1973)	Weighting-scaling checklist for evaluation of impacts of alternatives.
Dee, et al. (1972)	Weighting-scaling checklist with a good listing of biological, physical-chemical, aesthetic and cultural variables.
Dee, et al. (1973)	Weighting-scaling checklist based on relevant matrices and networks. Ranges of scale values. Concepts of "environmental assessment trees" to account for interrelationships among environmental factors.
Dunne (1977)	Weighting-scaling checklist for sanitary landfill site selection.
Gann (1975)	Weighting-scaling checklist using paired comparison technique is described.
Lower Mississippi Valley Division (1976)	Weighting-scaling checklist using habitat approach is presented.
Morrison (1974)	Weighting-scaling checklist using paired comparison technique is described.
Odum, et al. (1971)	This weighting-scaling checklist includes an error term to allow for misjudgment in the assignment of importance weights. Computerization of the methodology enables the conduction of a sensitivity analysis.
Paul (1977)	Weighting-scaling checklist used to prioritize potential projects.

Table VIII.22: Continued

Author(s)	Salient Features
Raines (1972)	Weighting-scaling checklist; use of functional curves to translate environmental impact quantities into environmental cost units.
Salomon (1974)	Weighting-scaling checklist; relative scaling based on a reference alternative is used.
School of Civil Engineering and Environmental Science and Oklahoma Biological Survey (1974)	Weighting-scaling checklist, which is similar in concept to Dee, et al. (1972); an error team is included to account for subjective misjudgments.
Smith (1974)	Weighting-scaling checklist for a rapid transit system.
Toussaint (1975)	Weighting and scaling of 14 water pollution parameters was established by the Delphi procedure using two separate groups of 9 experts.
Wenger and Rhyner (1972)	A stochastic computer procedure is used to account for uncertainty in the weighting and scaling checklist procedure for evaluation of solid waste system alternatives.

Table VIII.23: Delineation of a Methodology for Trade-off Analysis Involving Environmental Impacts

Element	Delineation
A. Establish Interdisciplinary Team	**1. Selection**
	(a) Select members of interdisciplinary team.
	(b) Designate team leader.
	2. Review and Familiarization
	(a) Review information on potential technologies.
	(b) Visit locations with technologies being applied.
B. Select Decision Factors and Assemble Basic Information	**1. Selection**
	(a) Assemble preliminary list of decision factors.
	(b) Use technical questions and findings from A.2, along with professional judgment, to select additional relevant factors.
	(c) Identify any resulting interactive or cross-impact factors or categories.
	2. Environmental Inventory
	(a) Assemble extant baseline data for selected factors.
	(b) Identify factors with data deficiencies, and plan data collection effort.
	(c) Conduct field studies or assemble information on data-deficient factors.

Table VIII.23: Continued

Element	Delineation
C. Evaluate Alternatives Relative to Decision Factors	1. Prediction and Delineation
	(a) Predict changes in each factor for each alternative using available techniques and/or professional judgment.
	(b) Delineate potential impacts of alternatives.
	(c) Highlight significant impacts and "red flag" any critical issues.
	2. Weighting and Scaling
	(a) Use paired comparison technique, or some other importance weighting technique, to determine importance coefficients for each factor (FIC).
	(b) Scale/rate/rank predicted impacts through development of alternative choice coefficients, or use of some other technique for evaluation of alternatives relative to decision factors (ACC).
	3. Evaluation and Interpretation of Results
	(a) Multiply FIC by ACC to obtain final coefficient matrix. Sum coefficient values for each alternative.
	(b) Use values in final coefficient matrix as basis for description of impacts of alternatives and trade-offs between alternatives.
	(c) Discuss any critical issues and predicted impacts.
D. Document Results	1. Rationale
	(a) Describe rationale for selection of decision factors.

Table VIII.23: Continued

Element	**Delineation**
	(b) Describe procedure for impact identification and prediction, and rationale for weighting, scaling/rating/ranking and interpreting results.
	2. Provide Referencing of Sources of Information

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